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POTENTIAL FOR CASCADING WOOD FROM BUILDING

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 20 August, 2014.

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Abstract of master's thesis

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Abstract

There has been a growing interest in cascading materials recovered from buildings as the amount of construction and demolition waste (C&DW) has been increasing. In Finland, cascading wood from building can be one of the effective approaches considering that there are a lot of wooden buildings, which are now due for renovation or demolition. From this point, investigating the available amount, as well as the potential for cascading, is significant. However, the statistics available to discuss the potential are limited at the moment. Therefore, this study aimed to obtain the required data through a case study of a building demolition and to analyze the potential of cascading wood from the building.

The case study building was a wooden building (Kindergarten) in Porvoo. The possible amount for cascading was calculated before the demolition and compared with the amount after the demolition. Following this, the wood recovered from the building was assessed from different perspectives. Through the data gathered, the potential amount for cascading was obtained and the amounts were compared in terms of the cross-section and the location where each recovered wood piece was used. The results revealed that each recovered wood piece showed different behavior in the extent of damage, regardless of the dimension. In addition, wood with better condition was recovered in the independent parts such as the roof and exterior cladding, which also showed different behavior by location. These results indicated that the cascading potential for recovered wood should be discussed in terms of both cross-section and location.

Through the further investigation, even smaller cross-section such as the 1”× 4” from the roof board and the 1”× 4” and 1”× 6” with paint from the exterior cladding showed a high cascading potential thanks to the reasonable recovered condition. Moreover, it could be observed that the paint was not necessarily critical for cascading unless it is hazardous. These results demonstrated the potential of the extension of a target for cascading recovered wood not only to wooden building but also other types of buildings with concrete or steel structures. It was also discussed that technological aspects such as the demolition method and building design extensively affected the potential. At the same time, however, it was suggested that minor changes in the details could be applicable to improve them for the enhancement of the potential. To raise the reliability of the results from this study, more case studies with different types of buildings were recommended. In addition, more accurate cost comparison and environmental assessment including whole lifecycle would be beneficial to drive the industry in the direction to cascading more materials recovered from building in general.

Keywords Cascading, Recovered wood, Demolition

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I hope this thesis will contribute to open a door of this topic for the future and we can continue this project further.

Espoo. August, 2014

Daishi Sakaguchi

Table of contents

1 INTRODUCTION

1.1 Background

The amount of construction and demolition waste (C&DW) has been increasing and there are growing demands for the reduction of C&DW. Following this trend, the cascading of recovered materials has been actively discussed. The core issues in this discussion are to set out the appropriate strategies for C&DW management, to reduce environmental impact and to raise efficiency as a material resource.

When considering this topic, the strategies should be carefully considered in each case because each country has different C&DW situations. In the Finnish case, wood recovered from building has been used as an energy resource. However, this recovered wood could be utilized in higher value products and it could be one of the potential approaches since there are a lot of wooden buildings in Finland and many of them are now due for renovation or demolition (Peittilä, 2014).

There are statistics available about the amount of C&DW from construction in Finland (Kojo and Lija, 2011; Pirhonen et al, 2011; Peittilä, 2014). This information enables us to understand an overview of the situation of C&DW in Finland. However it is nearly impossible to analyze them in more detail due to a lack of information. The lack of data has to be made up for to observe the potential for cascading wood in Finland.

To discuss the potential, it is necessary to understand more detailed factors about recovered wood in building, such as the available amount, the types, the dimensions and the condition. With this information, possible cascading chains in Finland can be investigated and the prospect for the cascading of recovered wood in Finland can be discussed as well.

1.2 Aim and Objectives

The aim of this study was to observe the condition of recovered wood from buildings and assess the potential for cascading of the recovered wood. The detailed information provided by this study could also be a starting point to establish a database of wood recovered from construction in Finland.

The detailed information was gathered from a case study of an actual building demolition because it provides a better understanding of the real situation of demolition and also yields more precise data.

The following issues were assessed and discussed in this study.

- The actual amount of recovered wood from building demolition
- Detailed information of recovered wood
- The potential for the cascading of recovered wood
- A consideration of how to enhance the availablity of recovered wood

1.3 Scope and structure of this study

In the previous researches, a variety of strategies related to waste management, building design and material use in buildings have been discussed with a view to enhancing the possibilities for cascading. These strategies are crucial to encourage different stakeholders to consider cascading of not only recovered wood but also of recovered materials from building construction in general.

However, all of these strategies do not necessarily suit the Finnish situation. This indicates that the appropriate strategies should be defined in a Finnish context. For this reason, the importance of an actual case study is also emphasized and the strategies will be discussed according to the results of the Finnish case study.

In Finnish buildings, light-frame wooden structure had been used extensively, particularly after World War II (Norri and Paatero, 1996) and many of the building from this period have been renovated or demolished by now (Peittilä, 2014). In addition, wood construction has been promoted in both small and large scale building as is the current trend in Finland (Leftinen,2012).

From these situations, it can be expected that more wood waste will result from both renovation and demolition in the future. To meet this expectation, an actual demolition of a wooden building was chosen as the case study in this work.

This study is structured into four steps as follows.

1. A review of previous research about cascading and related topics
2. An explanation about practical information of the target and method
3. An site assessment of the case study building and analysis of the data
4. A discussion of the potential for cascading wood in Finland

The first part, which forms the Literature review, Chapter 2, is a review of the existing research concerned with cascading, waste management, the properties of recovered wood as well as the existing solutions to enhance the cascading of building materials. In this part, the different cases, strategies and solutions in each country are also examined.

In the second part, Chapter 3, the target and method of the case study are explained with practical information about the case study building. Pre-observation of other demolition project prior to the demolition of the case study building was conducted to consider reasonable monitoring methods for building demolition in the Finnish situation. According to this observation, an applicable and reasonable monitoring method was suggested.

A pre-calculation of the wood products used in the target building was also done before the demolition started. By this calculation, the possible amount of recovered wood was estimated and compared with the amount obtained.

Following the second part, in Chapter 4, the matter of the case building demolition study are presented, and the data collected is assessed in the third part. Through the case study, the demolition process was monitored from the beginning to the end and the recovered wood from the demolition was analyzed.

In the fourth part, Chapter 4, the potential for, as well as the barriers to the cascading of recovered wood, are discussed according to the results of the case study. This discussion includes the actual situation of wood recovered from demolition in Finland, suggestions for the enhancement of available recovered wood and the potential cascading chains.

In addition to the above, the cascading of recovered wood and recovered materials from construction in general are investigated together with broader topics from different points of view for the facilitation of cascading. Furthermore, topics for future research are discussed with the contents above.

2 LITERATURE REVIEW

2.1 Necessity for cascading and legislation

According to Kammerhofer (2012), the term cascading applied to wood the same biogenic resources are used sequentially: first (and possibly repeatedly) for material applications and then for subsequent energy applications. The longer the sequential process is, the longer the wood products can store carbon in them. It is crucial for cascading to set a clear path for utilization according to the performance and quality of wood products.

The clear reason for the necessity for cascading recovered materials in Finland is the low recycling rate of construction and demolition waste. The recycling rate in Finland is less than 40%, which is one of the lowest in the EU along with Cyprus, Greece, and Spain (Ganguly, 2012). Compared with central European countries such as Austria, Belgium and France, the Finnish recycling rate is so low that it will require more effort to meet the target set by the EU and also to reconsider the ways of waste management.

2.1.1 Possibility and facilitation for cascading recovered wood

It would make sense to cascade recovered wood in Finland because most single family houses have been built of wood. The market share of wooden houses accounts for over 80% of wood frame structures. In addition, the Finnish government has lately promoted wood construction following an expansion of the wooden building share in Sweden (Leftinen, 2012).

More availability of recovered wood can be expected in the future and wood has a lot of potential to be cascaded at different scales and in different applications. There are three important principles of resource cascading; appropriate application, life time extension and quality-conservation (Fraanje, 1997). Figure 1 shows an example of the cascading flow for wooden products.

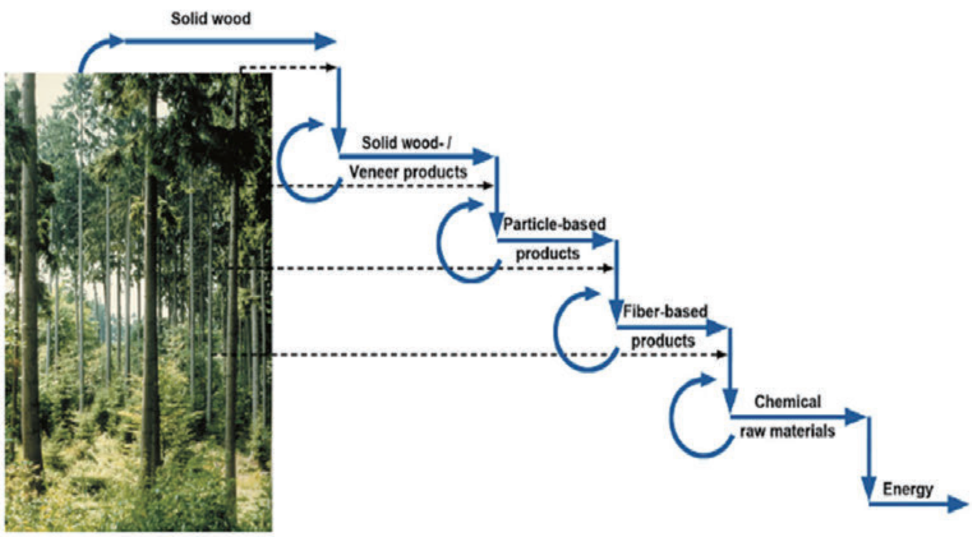

Figure 1. Cascading of wood (adopted from Höglmeier et al, 2013, p.82)

In the Japanese case, recovered lumber from demolished post and beams have been found to have relatively larger dimension and be in good condition such as no significant damage and less attached materials. This clearly shows the potential for the recycling and reuse of lumber recovered from building (Nakajima and Futaki, 2001).

Gustavsson et al (2006) assume that 90% of lumber, plywood and particleboard could be recovered from the wood buildings they examined in Sweden and Finland. The percentage could be raised by facilitating the reuse and recycling of wood buildings with disassembly design and deconstruction methods.

According to research in Bavaria, Germany, 26% of recovered wood would be suitable for reuse and 27% for other high value secondary product. This percentage could be enhanced more by adjustments to legal regulation especially in the reuse of structural components (Höglemeier et al, 2013).

2.1.2 Legislation in different countries and regions

The EU

As a current trend, C&DW has likely been increasing in the EU. A new policy in the EU was introduced by the Waste Framework Directive (Directive 2008/98/EC) stating that 70 percent by weight of C&DW should be reduced by 2020 and utilized in preparation for reuse, recycling and other material recovery strategies. To prevent waste increase, a common definition for C&DW in the EU is necessary to facilitate appropriate management (Sonigo et al, 2010 and Sáez et al, 2011).

UK

In the UK, strategies for C&DW management was set by Vadera et al (2008) after the Waste Strategy for England (2007). Following the regulations by the EU, the UK has also been benchmarking to set a clear target. One of the common problems for C&DW in the UK is the amount of landfill and carbon emission from C&DW. Therefore, the legislation currently focuses on a reduction in the amount of landfill and emissions (Vadera et al, 2008).

USA

There is no specific target in the US either, however goals for C&D waste reduction and utilization have been set by the U.S. Environmental Protection Agency. This goal aims to focus on specific fields such as research on C&DW materials, the promotion of practices for C&DW reduction and recovery, and cooperation with stakeholders (EPA, 2014).

Japan

In Japan, the regulations for C&DW have been set into construction material recycling law (2000). This law focuses on the waste related to concrete, asphalt, wood, and steel as the target wastes. It requires contractors or demolishers to recycle the target wastes in the case that the building is larger than the standard (80 m^2 of floor area for demolition and 500 m^2 for new construction or extension, for instance). The goal for the recycling rate was set of 95% by 2010.

2.1.3 Classification of wood waste

One of the obstacles in the cascading of recovered wood is the current classification of wood waste. Table 1 shows a comparison of the classification in different countries.

Table 1. Comparison of different classificaition of wood waste in different contries

Sources	Scope	Definition	Other comments
Finnish classification (A,B,C,D) [1)]	Used wood/Recovered, construction/demolition wood	Clear sepation for clean wood (Wood pallets and wood residues for new building) and contaminated wood (demoltion wood and impregnated wood)	Clean and contaminated Energy oriented
German Classification (A Ⅰ, A Ⅱ, A Ⅲ, A Ⅳ, PCB) [2)]	Used wood	Used wood from solid wood as well as timber-based products, composited with more than 50% of wood. PCB treated wood is strictly separated.	Chemical and mechanical contaminations
WRAP wood waste grades in UK(A,B,C,D) [3)]	Used wood/Recovered, construction/demolition wood	Clear sepation for clean wood and contaminated wood (demoltion wood and hazardous wood) from a variety of sources	Chemical and mechanical contaminations
Guidline for recovered wood in Japan (A,B,C,D) [4)]	Recovered wood from building	Classification by dimension and contaminations such as CCA, paint and metals	Chemical and mechanical contaminations, dimension

1) Alakangas and Wiil (2008), p.42, Pirhonen et al, p.18-19 2) Höglemeier et al 2013, p.83, Deroubaix (2014), p.15
3) WRAP (2012), p.21 4) The Committee for the promotion of recycling of construction by-product (2008), p.22

In each country, the number of categories in wood waste is almost the same; A: clean, B: some non hazardous paint or contamination, C: non hazardous paint or modification, D: hazardous. In Finland, the classification is defined only for energy recovery even though recovered wood could be utilized in higher value products. The deference between Finland and other countries is that other countries aim to utilize the waste as the resource for board products before wood waste is used for energy recovery. However, it can still be said that these classifications are not suitable for cascading wood in higher value products.

2.2 Wood waste from construction and management

2.2.1 Wood waste from C&DW

Wood waste can be cascaded for a variety purposes such as reuse, reprocessing and recycling, if the quality of the recovered wood is sufficiently high. Recovered wood is commonly used for energy production in Finland though. Figure 2 shows the amount of waste from construction, renovation and demolition in Finland. According to the figure, wood waste accounts for 600,000 t/a of total waste, which is the major part of C&DW in Finland. In the wood waste category, waste from renovation accounts for approximately 70% of the total, which is still controversial (Peittilä, 2014). However, the total amount of wood waste itself clearly shows the potential for cascading even though the amount from each source needs to be confirmed by the further investigations.

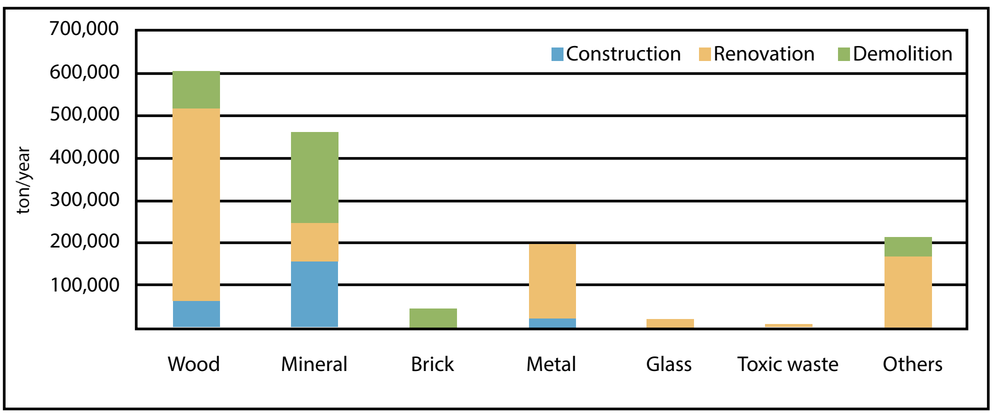

Figure 2. Amount of waste from different source (adopted from Kojo and Lija, 2011, p.24)

Table 2 shows a comparison of waste from construction and renovation. As a general trend, the percentage of wood waste from renovation is significantly higher than from construction. This means that roughly 40-60% of renovation waste consists of wood.

Table 2. Amount of waste from different source (adapted from Peittilä, 2014, p.82)

New construction		Source	Renovation			
Ruuska 2013, p. 78	GreenNet Finland 2005 pp. 9		GreenNet Finland 2005 pp. 9	Perälä 2004, pp. 15 Building and housing	Perälä 2004, pp. 15 housing	Perälä 2004, pp. 15 building
27.0%	23.0%	Wood	46.0%	51.0%	63.0%	40.0%
59.0%	68.0%	Mineral	9.0%	10.0%	12.0%	7.0%
12.0%	9.0%	Metal	21.0%	19.0%	17.0%	21.0%
2.0%	0.0%	Other	25.0%	21.0%	9.0%	32.0%

However, there is some uncertainty left in this percentage compared to the percentages from Figure 2. In Table 2, the percentage of waste from renovation is between 40-63% even though it was 70% in Figure 2. Peittilä (2014) pointed out one reason for that is that tracking the waste from renovation is challenging because the waste can be easily mixed up with other waste from different sources.

2.2.2 Wood waste management

The importance of waste management is emphasized even more in the case of wood waste since wood needs to be more carefully treated for cascading. An appropriate management can lead to a reduction in damage and an increase in the available wood at the same time.

In wood waste management, the separation between clean and dirty wood is important for effective cascading (Jeffrey, 2011). In this case, “clean“ means wood which does not have additives such as glues, resins, plastics and other materials. The importance of the deconstruction method has been emphasized by Falk and DeVisser (1999) because the method can possibly give a deterioration in the grade of lumber by nail holes and damage to the edges.

Figure 3 shows C&DW generation and treatment in Finland. Others categories include gypsum, glass, plastic, packaging, mixed waste and hazardous waste (Meinander, 2012).

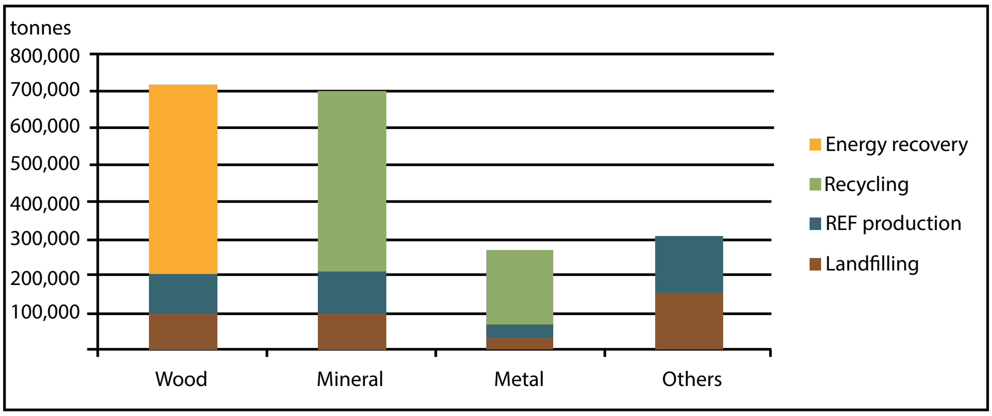

Figure 3. C&DW generation and treatment in Finland (adapted from Meinander et al, 2012, p.26)

According to this statistic, over 80% of recovered wood is used for energy production and not commonly used for recycling as secondary products. This result also means that recovered wood is simply chipped and burned as bio fuels whether it has sufficient dimension or condition for cascading or not.

Table 3 shows the situation of C&DW in the Japanese case. The recycling ratio of wood waste has been decreasing and reached less than 40%. This is a relatively lower percentage because it does not include thermal recovery. If thermal recovery is counted as recycling, the ratio reaches 80% (Nakajima and Futaki, 2001). Even though the recycling ratio in Japan is higher than in Finland, utilizing wood waste in energy production is still more common and new strategies are required to improve this situation.

Table 3. Type, amount and recycle ratio of C&DW waste in Japan (adapted from Nakajima and Futaki, 2001, p.4)

Type of waste	1991		1996		2001	
	Weight (million tons)	Recycle ratio (%)	Weight (million tons)	Recycle ratio (%)	Weight (million tons)	Recycle ratio (%)
Construction waste	-	42	99	57	85	81
Asphalt	-	50	36	81	30	98
Concrete	-	48	36	65	35	96
Mixed	-	31	10	6	5	7
Wood	-	56	6	40	5	38
Soil and rock	-	21	10	6	8	30

2.2.3 Advantages of wood waste management

Three important reasons to manage wood waste are saving landfill cost and space, reducing environmental impacts as well as saving natural resources (Solid Waste Association of North America, 2002).

According to eight different case studies in the US, about a third of urban wood waste and demolition waste can be recovered for subsequent use. In addition, wood waste recovery has a generally positive effect on environmental impact even though some environmental issues need to be investigated further (Solid Waste Association of North America, 2002).

About wood waste in Japan, wood chips can be produced from good quality wood waste or large dimensional lumbers obtained from building demolition. The total amount of building waste can also be reduced by using recovered wood for building wall structures (Nakajima and Futaki, 2001). It has also been shown that diverse utilization of waste and a higher reuse rate can result in a reduction in the total amount of waste and the consumption of new wood materials (Hiramatsu et al, 2002). Similar results have been reported from a comparison of concrete block wall and wooden wall, and a wooden wall can reduce waste far more during demolition (Peuportier, 2001).

Moreover, recycling wood waste from building demolition can contribute to more effective waste management and make up for a lack of natural resources at the same time. Another benefit is that recycling wood waste can store carbon longer, which will result in lower atmospheric emissions regarding global warming (Obata et al, 2006). Recycling wood as biofuels are becoming more common nowadays globally.

2.3 Benefit of using wood recovered from building and examples

2.3.1 Benefit of using recovered wood products

Recovered wood can be utilized as the source of different wood products according to the condition. It can potentially reduce the amount of material resource and the energy need for manufacturing. Considering emissions, carbon can be stored in wood products longer if they are cascaded as secondary products (Miyazaki et al, 2003, and Bill, 2006). In addition, the cascading of recovered wood contributes to a reduction in construction waste (Miyazaki et al, 2003, and Design for reuse primer, 2010). These two aspects can be considered to be the biggest advantages for cascading recovered wood.

2.3.2 Use in structural parts

Using recovered wood for structural elements is an almost direct use from a previous building to a new one. It can result in space savings and the least energy consumption for reprocessing and less environmental impact, particularly if it is directly reused on site (Solid Waste Association of North America, 2002).

For structural use, however, using recovered wood faces stricter requirements. Recovered wood needs to be strong enough to sustain load. In addition, it has to keep the properties stable. Recovered wood is generally dried well so that the moisture content is at the equilibrium state, which is appropriate for secondary products and saving on the drying process (Miyazaki et al, 2003).

The compression strength of recovered wood is generally higher than that of new wood (Ooka et al, 2008, Hirashima et al, 2004b and Yamasaki et al, 2005). The only concern for structural application is the brittle tendency of recovered wood (Kohara, 1952, 1954a).

2.3.3 Use in non-structural parts

In non-structural parts, special properties are not required. As for use in interior finishes, the visual properties of recovered wood (the color and atmosphere) are more important (Figure 4a). The visual properties are also important in the exterior uses shown in Figure 4b. For ceiling and floor paneling, the same things can be mentioned.

Figure 4a. and 4b. Examples of secondary use in building (adopted from Design for reuse primer, 2010, p.16,18)

For exterior use, extra care will be required because ultraviolet rays and moisture will cause attack of wood used outside, and the properties of wood can be generally degraded (Feist, 1990).

The surface condition and color will especially be affected even if some treatments or modifications are applied to the surface. To facilitate reuse of wood on the exterior, more studies and a regulation or certification system for recovered wood are required.

2.3.4 Actual case of using recovered wood in building

Design for reuse primer (2010) introduces buildings using recovered materials in a variety of components, and an analysis regarding how much recovered material was used in the project. It was mentioned that most of the available recovered wood was old growth lumber, and it often has greater quality and durability than the newer woods in the market. Table 4 shows one of the examples in a town center located in Portola valley, CA, the USA.

Table 4. The original use and reuse application (adapted from - Design for reuse primer, 2010, p.19)

Material	Source	Original use	Reuse application
6*10 dimensional lumber	On-site	Beams	Beams
2*6 Douglas Fir	On-site	Roof decking	Interior paneling
2*6 Douglas Fir	On-site	Roof decking	Ceiling paneling
Glu-lam beams	On-site	Beams	Contertops
Blue-gum Eu-calyptus trees	Portola Valley,CA	Trees	Wood flooring
Redwood	Crescent city	-	Exterior siding
Alaskan Yellow cedar	Winthroop,WA	-	Sunscreen louvers
12″-16″ Alder trees	On-site	Trees	Cladding for steel columns

Over 90% (by weight) of the old buildings were reused in this project. The amount of available recovered wood for cascading depends on quite a few factors such as the original condition of the wood, economic issues and the design of the building. However, it can be effectively cascaded in new buildings.

2.4 Change and condition of recovered wood

Understanding the effect of aging and changes on each property is fundamental in terms of appropriate secondary applications and facilitation of the cascading process. The possibility of cascading recovered wood will be much greater if the quality of recovered wood is sufficiently high and stable enough.

2.4.1 Physical properties

The physical condition of recovered wood depends on the location and the condition of the use place. These factors can strongly affect the physical properties.

Visual properties

It has been observed that there was no significant visual difference between old timbers and new ones except the 2mm brown color surface (Kohara, 1952). Matuo et al, (2010) reported that the change in color by natural aging was similar to that of heat treated wood. This behavior was further investigated and confirmed as the effect of natural aging by Matuo et al (2011).

On the contrary, Falk et al (2000) found that a third of the old timbers from the World War II era were visually downgraded due to splits, or damage according to grading rules in 1996 by West Coast Lumber Inspection Bureau (WCLIB). Chini and Acquaye (2001) stated that in recycled lumber, 57% of the lumber was visually damaged because of its use, construction and deconstruction process.

Moisture content & Dimensional stability

The moisture content of old timbers was found to be lower than new timbers and recovered timbers had less shrinkage percentage compared to new ones (Kohara, 1952, 1953, and Erhardt et al, 1996). Kohara and Okamoto (1955) also showed that recovered wood had less moisture adsorption than new wood. This tendency was also supported by results from a comparison of new wood with heat treated wood.

Hirashima et al (2005), on the other hand, mentioned that 255 years old timber had about 1% more moisture content than new timber, but that, 115 and 290 year old timber had about 0.7, 1.5% more moisture content respectively than new timber. Recovered wood from a building used in an extremely cold climate was also investigated by Sekiguchi and Tanaka (2002). The plywood used in the interior wall had a lower moisture content and the adhesiveness was also higher. On the contrary, plywood used in the exterior wall had a much higher moisture content and much lower adhesiveness.

Insect damage

Saito et al (2008) states that insect damage is more critical than deterioration by aging. However, the value for the strength of the timber is not strongly affected by aging unless the timber has been subject to huge insect damage (Ooka et al, 2008). In another comparison, old timbers damaged by insect showed lower values of modulus of rupture (MOR) and modulus of elasticity (MOR) than those of undamaged wood (Ito and Hashizume, 2006).

2.4.2 Mechanical properties

Investigations on different mechanical properties of recovered wood from buildings are also crucial for the wider and adequate application of recovered wood.

Compression strength

A comparison of the moisture content and compressive strength of old and new timbers are shown in Figure 5. Old timbers showed more strength in compression tests (Kohara, 1952, Ooka and Izuno, 2008 and Ooka et al, 2011).

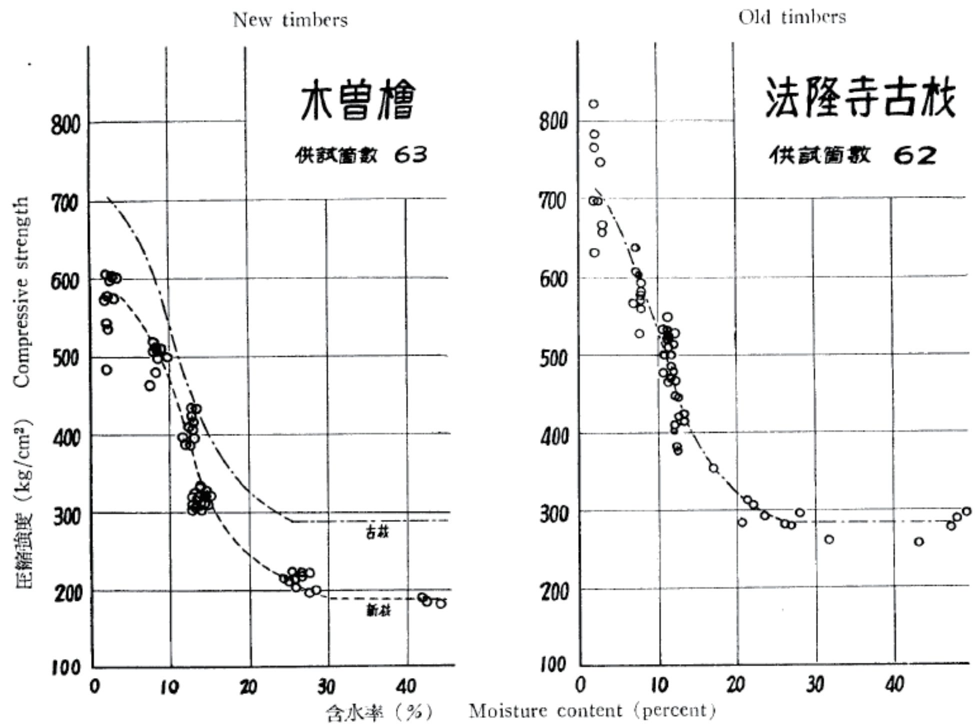

Figure 5. Moisture content and compressive strength (adapted from Kohara, 1952 p.124)

Kohara (1954a) also noted that the tendency for properties such as compression strength, bending strength, hardness, and Young's modulus to rise once as the timbers are aging, but they decrease (1-1500 year time scale). In the end, the properties were not significantly different from the original ones.

Ito and Hashizume (2006) stated that the average MOE of 130 year old timbers was almost the same as the value of 20 year old timber, whereas the average of MOR was significantly lower than the 20 year old timber. Yamasaki et al (2005) also state that the tensile strength was much lower than that of new wood.

On the other hand, Hirashima et al (2004b) also found that the ultimate compressive strength (UCS) and MOE of aged Keyaki wood decreased 10.8% and 14.2% respectively, whereas the UCS and MOE of aged Akamatsu wood increased 18.7-48.9% and 51.1-58.8% respectively. From this result, it can be said that the behavior on the strength is so dependent on wood species that the different behaviors could be observed by species.

Impact bending and shear strength

The impact bending and shear strength of old timbers have been found to be less than those of new timbers. The Young´s modulus of old timbers is higher than that of new timbers. This tendency means that timber will generally be harder and stronger with aging, but, it will become more brittle (Kohara, 1952 and Kohara, 1954b). Similar results have been found by Hirashima et al (2005) and Ooka et al (2008).

Chini and Acquaye (2001), on the contrary, found that the bending strength and modulus of elasticity of salvaged lumbers were higher than those of the new ones. A similar result was obtained from a comparison of the bending strength and Young's modulus of new and old wood, which showed that 167 year old and 155 year old timbers had the greatest value (Ooka et al, 2011).

The bending and shear strength is affected by natural aging. But, the behavior also depends on the species because each species has its own structure. Thus, it can be considered that the contradictions in the research was caused by these factors and further investigation on recovered wood of different species is required.

Figure 6 shows the interesting behavior of old wood by a comparison of the shear strengths of new and recovered wood. According to the experiments by Ando et al (2006), recovered wood has more tenacious behavior before its final fracture compared to new wood.

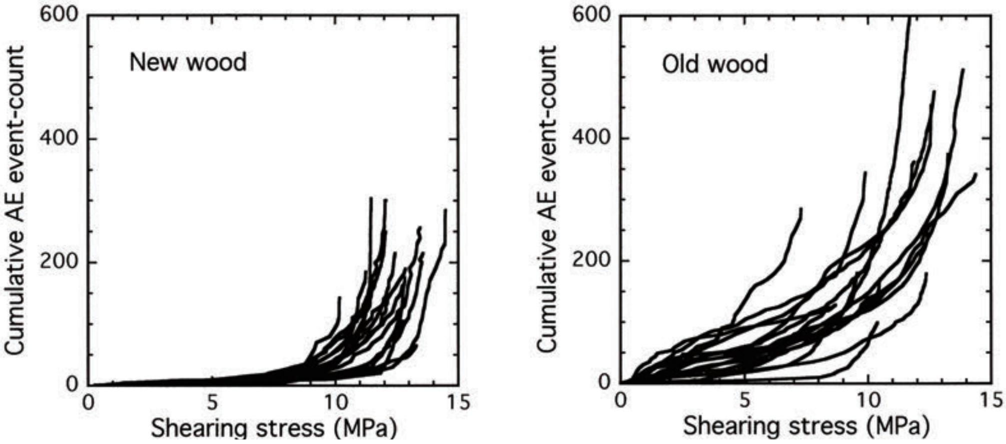

Figure 6. shear strength of new and recovered wood (adapted from Ando et al, 2006 p.485)

Tensile strength and elasticity

Yamasaki et al (2005) demonstrated that wood became stiffer and more brittle as it aged, thus this aspect needs to be considered when old wood is reused especially for structural purposes. The same results was also reported by Yokoyama et al (2009) and the results are shown in Figure 7.

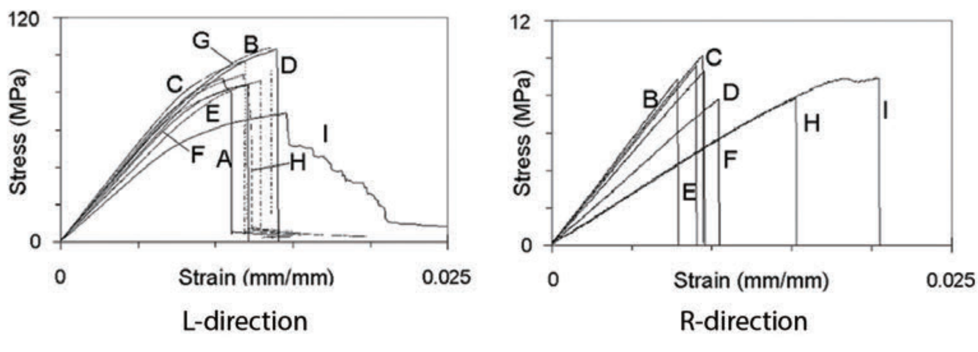

Figure 7. Stress-strain relationship of different recovered wood (adapted from Yokoyama et al, 2009 p.605)

The MOR and MOE of aged Keyaki wood decreased by 16.3% and 14.8 % respectively. However, the MOR and MOE of 270 years old Akamatsu wood increased by 17.3% and 10.8% respectively. These values also increased by 42.1% and 26.8% respectively in 290 years old Akamatsu wood (Hirashima et al 2005).

The ultimate tensile strength (UTS) and MOE of old Keyaki wood were 16.4 and 20.3% lower than that of new wood. However, the UTS and MOE of old Akamatsu wood were not significantly different from the ones of new wood (Hirashima et al 2004a). The ultimate shearing strength (USS) decreased by 7.1% in aged Keyaki wood, and increased by 10.1% in 290 years old Akamatsu wood. The ratio of the stress at proportional limit to the ultimate stress increased 15.1-28.3% in aged Akamatsu wood (Hirashima et al, 2004a).

Considering these results, it can also be said that the aged wood developed a brittle tendency with the lapse of time even though the aged wood showed higher values of strength in compression, static bending and shear strength (Hirashima et al 2005). Yokoyama et al (2010) also found similarities in the trend of properties, particularly rigidity, Young's modulus and the rupture energy of aged wood and heat-treated wood.

2.5 Technical solutions to enhance cascading in building

A variety of technical solutions have been discussed for the enhancing the cascading of recovered materials. When it comes to the cascading of building materials, appropriate disassembly design takes an important role.

2.5.1 Strategies at building scale

The life cycle of a building is much longer than usual products. The total amount of materials for building is also much bigger. Thus, the importance of cascading building materials has recently been emphasized more. However, there are still problems and barriers to facilitate cascading at the building level.

Gaisset (2011) states that there is a complex relationship among the construction stakeholders such as designers, constructors and clients because each has different aims. In addition, buildings are not generally meant to be reusable since most of materials are attached to others (Webster and Costello, 2005).

Crowther (1999b) pointed out that disassembly design for buildings can be profitable for cascading. However, it is not considered in the primary design and the old requirements might not meet future regulations. Furthermore, designers knowledge of disassembly design is lacking.

2.5.2 Problems and barriers

Here are the problems and barriers mentioned in previous research for the cascading of recovered materials from building (Crowther,1999a, 1999b, 2001, 2003 and 2005, Webster and Costello, 2005, and Gaisset, 2011).

1. Additional time and delay in scheduling
2. Limitation only to removal of a building
3. Actual estimation of deconstruction cost
4. Time and space for transportation, location and storage
5. Increase in costs and embodied energy during transportation and sorting process
6. Different parts of the building with different life cycles
7. Involvment of different stakeholders such as clients, architects, engineers, conductor in the process
8. Different goals by all stakeholders for a project from financial, environmental, social, and cultural point of views
9. Building not designed for easy disassembly
10. Work safety, health hazards, risk of site storage
11. Timing of design decision
12. Small market for secondary products from recovered materials

The principals and solution for disassembly design

Disassembly design for building is a broader definition including different aspects such as building design, material use, and demolition method.

Figure 8 shows one example of the strategies for disassembly design to establish a closed loop as a sustainable life cycle system for building materials (Crowther, 1999a). The recovered material should ideally be cascaded from the higher value products to the lower value products. By cascading materials appropriately, the cycle can finally function as a closed loop.

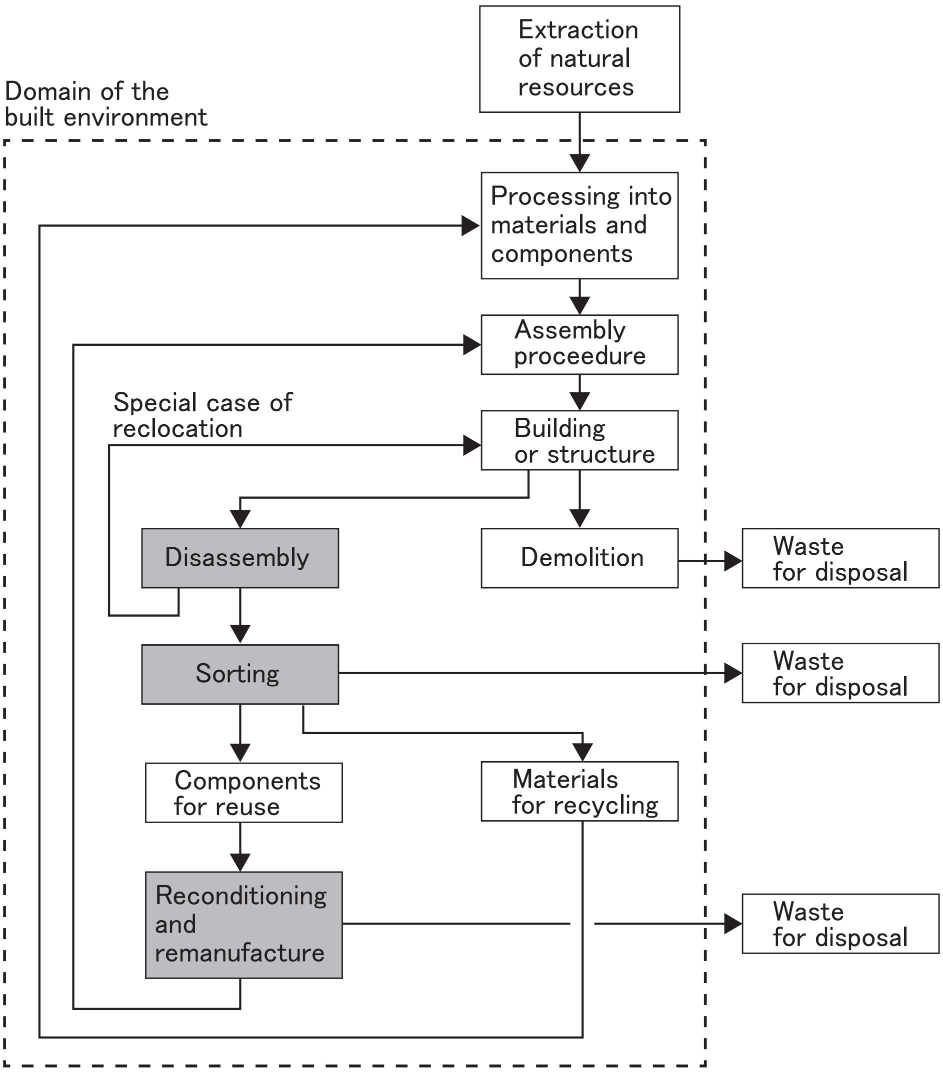

Figure 8. Strategy for building disassembly (adapted from Crowther, 1998 p.5)

Crowther (2001) states that the strategies for disassembly are strongly related to the four possibilities of reincarnation; recycling of materials, reprocessing of materials, reuse of components and relocation of whole building. It was concluded that each building would ideally be designed for component reuse or total relocation during the primary design process, and it is required to apply appropriate strategies to each case.

Pulaski and Hewitt (2003) reported that 25-30% of total waste/year came from building demolition in the USA and the UK. Considering the percentage of waste from the building sector, the scope of recycling after the life cycle also needs to be considered in the primary design process (Thormark, 2001). Guy (2003) also mentioned that through building disassembly design, appropriate recovery of building components from deconstruction can be achieved, and building materials will be effectively reused or recycled according to cost efficiency.

A similar suggestion is that new buildings should be designed for later deconstruction in advance. The effective method for the efficient deconstruction is to maximize the quantity of materials that can be recovered with minimal damage. This type of design can be better facilitated by a specific inclusion within environmental assessment methods (Tingley and Davison, 2011).

For instance, the cost and quality, considering the case that recovered wood is obtained from beams in old building, can be estimated by the joint system and the number of nails, screws or steel plates used. This indicates the importance of consideration during the design process, which enables much easier and more efficient disassembly.

Applying these suggestions may result in more work and cost in the initial stages of design. However the suggestions are worth considering because the final price and the quality of recovered materials from a building mainly depend on how much work is required to disassemble it and how the materials have been used in the building.

2.5.3 Principals and suggestions

Here are the principals and suggestions for building disassembly design mentioned in previous researches (Crower, 1999a, 1999b ,2001, 2003 and 2005, Guy et al, 2006, Guy and Ciarimboli, 2005, Thormark, 2001, Tingley and Davison, 2011, Gaisset, 2011, Webster and Costello, 2005, and Chiodo. J,2005).

I. Design for prefabrication, preassemble and modular construction
II. Simple and standardized connection details and less chemical connections
III. Simplifying and separating the mechanical, electrical and plumping (MEP) system
IV. Considering work safety during (de)construction
V. Minimizing the amount of components and materials in buildings
VI. Selecting fittings, fasteners, adhesives and sealants for quicker and easier disassembling
VII. Design to accommodate deconstruction logistics
VIII. Design for reusable and high valued materials
IX. Design for flexibility and adaptability
X. Documentation for disassembling methods and processes
XI. Design for worker´s movement, equipment, site access, points
XII. Materials and components for reuse on site directly
XIII. Disassembly design already at the primary design stage
XIV. Proper concept and principals applied in each project

2.5.4 Building disassemble method

In the case that timbers are used under normal conditions, the property values remain sufficient (discussed in 2.4). In addition to this, the quality and condition of recovered wood can be strongly affected by the disassembly and demolition method. Thus, appropriate demolition methods for each building type should be defined with a consideration of the cost, because budget is a limiting factor, and normal disassembly and sorting tend not to be feasible for cascading recovered wood on a low budget (Takayama, 2003).

In research by Nakajima, and Futaki (2001), the target housing was disassembled piece by piece. They stated that almost 9% of all recovered lumber could be re-used as structural lumber and 22% as lamella in glulam by their method. In addition, almost 73% of the lumber could be recycled as chips for pulp and boards. Miyazaki et al (2003) also proposed a hand-based dismantling method to maximize the material recovery efficiency as well as cost efficiency. This method is particularly effective for post and beam houses. Most of the recovered wood dismantled by this method, except the deteriorated wood, can be cascaded.

In Finland, the demolition method is mainly the grabbing and crushing. The method is decided by the operator of the machine. At first, some interior parts are demolished by hand. After that, each part of building is grabbed and crashed by machine (Figure 9a). Finally, the waste is separated and placed into each container (Figure 9b). The priority in demolition is on the efficiency and separation of each waste to minimize the processing cost.

Figure 9a and 9b Basic demolition method in Finland

In this chapter, existing research was explored from different point of views. First, cascading in general and the necessity, the related legislation in different countries and regions were introduced. Second, the situation of wood waste and the situation of wood waste management in different countries were observed. With those situation, the advantages of wood waste management were found. Third, different benefits by using wood recovered from building was shown with the actual examples. Forth, the changes in the properties of wood recovered wood from building was examined by different properties such as physical and mechanical properties. Finally, the existing technical solutions to enhance cascading building materials were shown.

In the next chapter, the information regarding a target building for a case study and an the assessment method will be introduced. The building information was gathered from the pre-visit to the case study building. The assessment method was defined through the pre-observation of C&DW management site and other demolition project with the investigation on the existing research.

3 MATERIAL AND METHOD

3.1 Method and approach

First of all, the situation of C&DW management and demolition in Finland should be understood to discuss the potential for cascading in terms of the recovered wood. In addition to this, detailed information regarding recovered wood needs to be gathered. The whole process for the assessment of demolition was as follows and it was undertaken in cooperation with Kuusakoski Oy.

- Pre-visit to C&DW management site
- Pre-observation of other demolition project
- Defining the assessment method
- Inventory of the case study building
- Assessment of recovered wood on site

3.2 Pre-visit and pre-observation

3.2.1 Pre-visit to C&DW management site

A pre-visit to a C&DW management site (Kuusakoski Ekopark in Espoo) was conducted to understand the whole stream of C&DW and the situation of classification. On the site, the separation for the wood waste was only if it can be a energy source or not. It was understood that wood waste needs to be separated into narrower classifications to cascade it in proper secondary applications. This aspect was taken into account to define classification criteria for this research.

3.2.2 Pre-observation of other demolition project

The demolition of one wooden single family house in Espoo was observed to determine a reasonable and applicable method. In the observation, the demolition method and the condition of recovered wood were mainly analyzed.

The findings were that board type wood products were almost always chipped or extensively damaged by the demolition. This indicated that board type wood products are not suitable for cascading. Different behavior was also observed in each cross-section. For instance, larger dimension wood (more than 2”×6”) was in relatively better condition and in longer lengths. On the contrary, smaller dimension (less than 2”×6”) was generally broken into smaller pieces. From this result, it can be expected that the classification by cross-section could be effective when considering cascading.

Another finding was the massive amount of wood recovered from a building, which indicates the difficulty in assessing all wood recovered from a building. This raised the necessity to consider the effective sampling method. Sampling should be undertaken with reasonable numbers of each wood recovered from a building to gather all required information.

3.3 Assessment method

3.3.1 Assessment method and classification on site

The principle assessment method is shown in Figure 10. The method was defined based on previous research and the results from the pre-observation of the demolition project in Espoo. The main assessment flow is introduced in this section and the criteria will be explained in section 3.3.2-4.

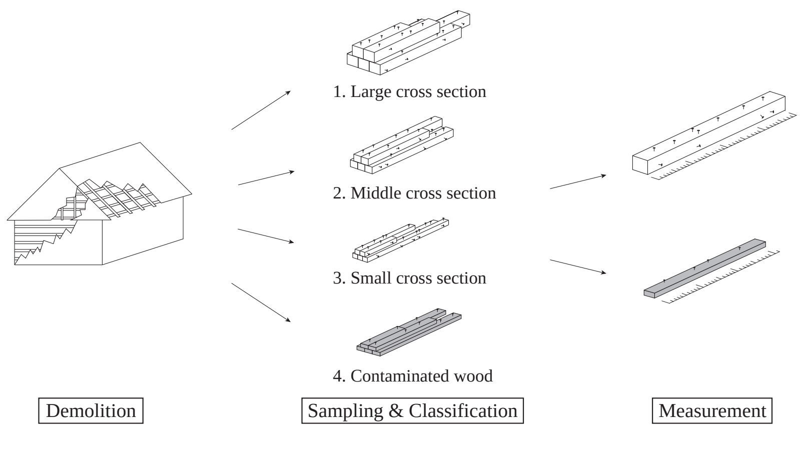

Figure 10. Assessment method on site

For on site assessment, accuracy is the most important factor. Considering the findings from the pre-observation, therefore, the target was set only for lumber types and 10 samples of each cross-section were randomly picked out from the piles demolished at the beginning. The piles included at least 5 elements each from different locations. Recovered wood with extra damage such as trampling or crushing by the machine was excluded. After recovered wood was sampled, it was classified by cleanliness and cross-section according to the criteria shown in Table 5.

Table 5. Classification criteria of recovered wood

	Quality			
Class	Clean and extent of damage			D: Contaminated
Cross section	A: Minimal (N<10 nails/m)	B: Less (10≦N≦20 nails/m)	C: Damaged (20 nails/m≦N)	
1. 2”×8” ≦ D				
2. 2”×4”≦ D < 2”×8”				
3. D < 2”×4”				

Following the classification, the length and the extent of damage such as number of nails and crack length were measured. All samples were measured before they were put into the containers. Using these steps, data about recovered wood from the demolition should be accurate and the total amount could be estimated.

3.3.2 Classification criteria - Cleanliness

As discussed in 2.1.3, each country basically separates wood waste into “clean” wood (unmodified and not contaminated) and “contaminated” wood (modified, coated, painted, deteriorated or other materials attaching) for chipping. In this research, recovered wood was first separated if it is clean or contaminated.

3.3.3 Classification criteria - Cross-section

As for the dimensions of the cross-sections, the classes were defined by the results of the pre-assessment 1: bigger cross-section, 2: middle size, 3: small size. Generally speaking, wood in bigger cross-section has higher the potential for cascading in the case that lumber is recovered with minimal damage.

3.3.4 Classification criteria - Extent of damage

The extent of damage is also critical. Evaluation of the damage was determined based on the work of Miyazaki et al (2003). They reported that the average number of nails per meter was 11 and the Young's modulus of all recovered wood in a clean condition satisfied the regulation for the structural purposes. Thus, the number of nails for the highest quality was set at less than 10 and the categories were defined as follows; A: less than 10 nails per meter, Class B: 10 to 20 nails and Class C: more than 20 nails.

Crack damage was also checked according to the standards (Figure 11) used in Miyazaki et al (2003). The extent of damage by deterioration should not be significant and should not cover a large area. Classes A and B should also fulfill these standards.

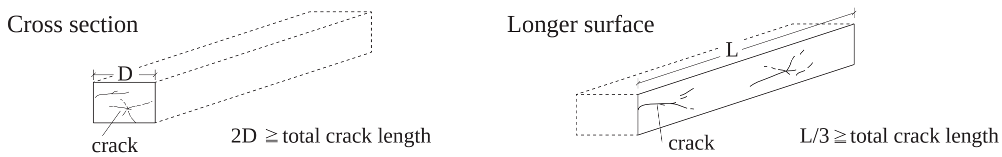

Figure 11. Standard for crack length

3.4 Information about case study building

3.4.1 Building information

The case study building had been used as a kindergarten (Näsin Päiväkoti). This kindergarten building was demolished due to air problems caused by mold. The building was mainly built with a wood structure and there were steel pillars and beams for joining each element (the size of 1 element was 3×6 m).

The elevation and section details are shown in Figure 12. The images of the building are attached in Appendix 1 (Näsin Päiväkoti in Porvoo).The functional floor area was 864 m^2 (only the atrium part was excluded due to a lack of information). The building was built in 1977 (the latest renovation was in 1996).

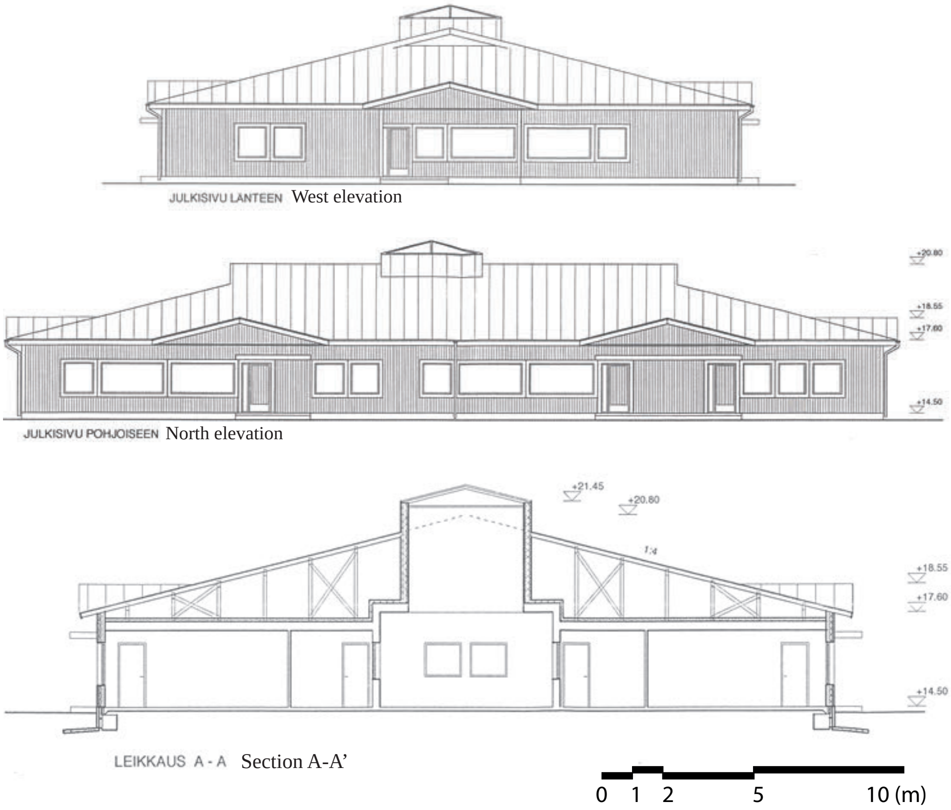

Figure 12. Elevation and section of case study building

3.4.2 Inventory of case study building

The structure of the case study building was checked on the site before the demolition started, since the detailed drawings for the building were not available. The inside of each element was individually opened to observe the members and to measure the dimension of each member (Figure 13). Through detailed observation, the required data were collected and the structure of each building is illustrated in Figure 14. The floor plan is also attached as Figure 15. Based on this data, the length of wood in each element were individually measured from the drawings and the total amount of wood was calculated.

Figure 13. Details of internal and extermal walls

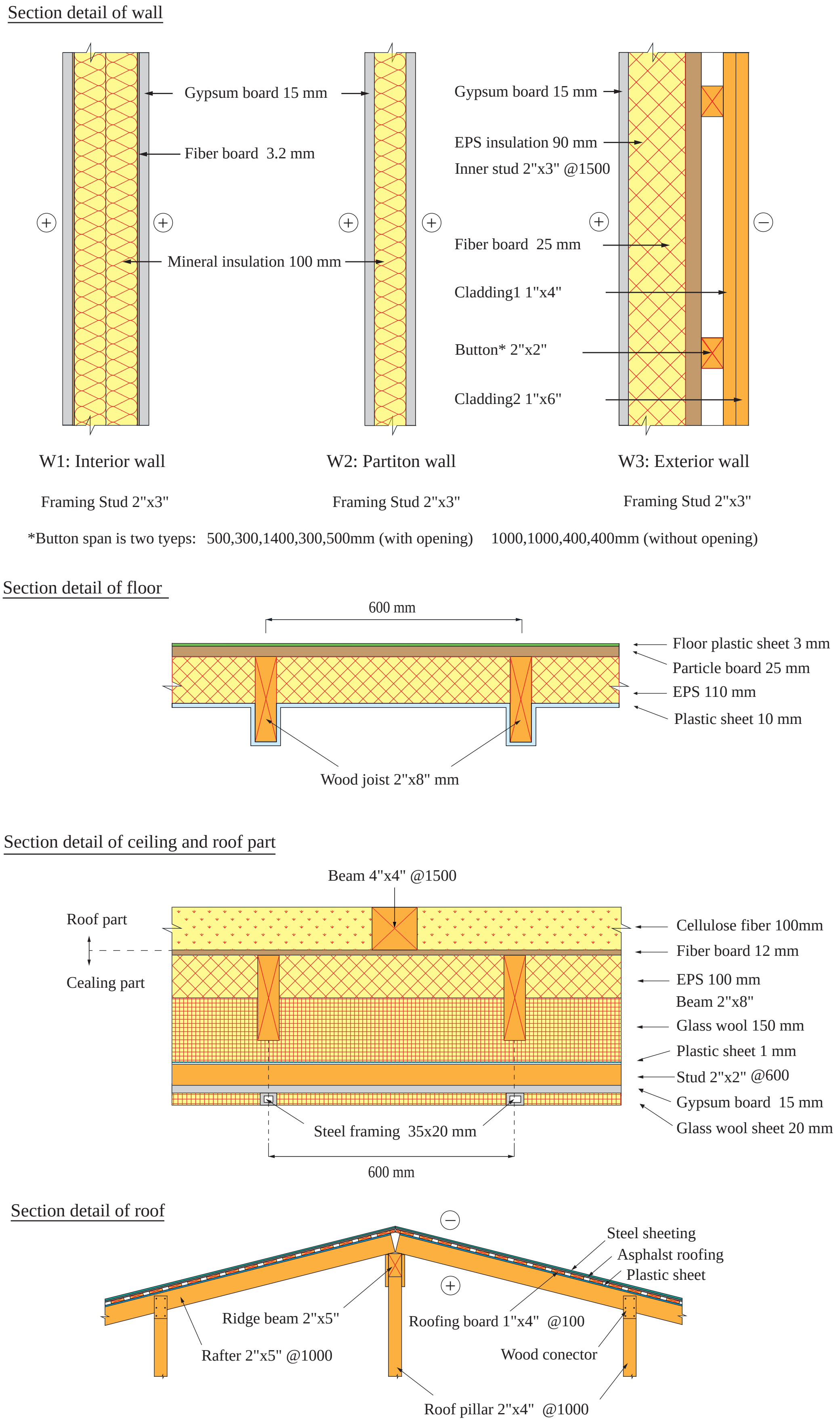

Figure 14. Structure of each element

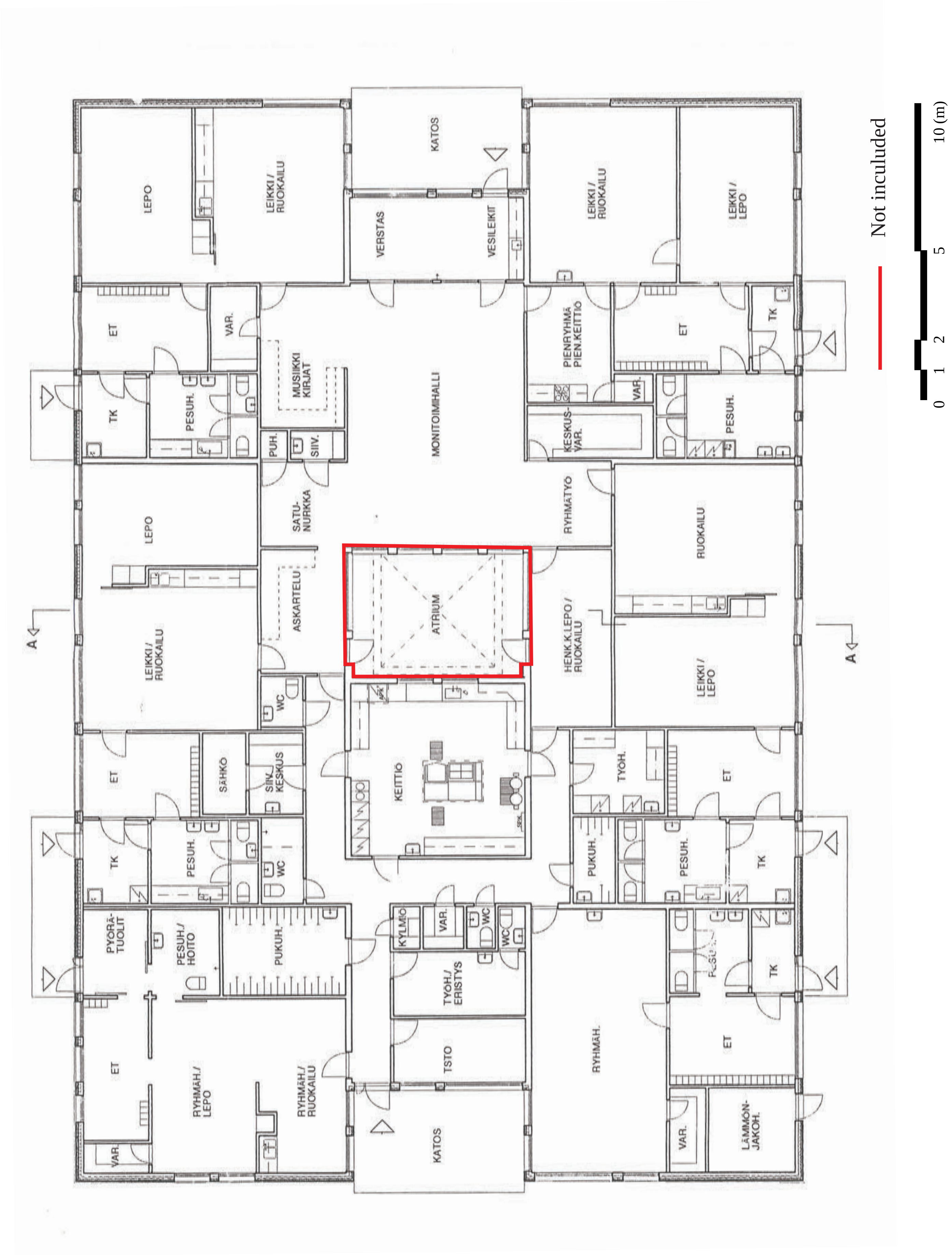

Figure 15. Floor plan of case study building

3.4.3 Demolished area for assessment

Figure 16 shows the demolished area in the assessment and each recovered wood was sampled from these areas. 10 recovered pieces of woods for each cross-section were randomly and individually sampled.

Figure 16. Demolished area in each element

Detailed information from monitoring the demolition, as well as the calculated data about the recovered wood will be presented in the next chapter with the discussion. The calculation is conducted by the data through the on site assessment of the wood recovered from the building demolition such as the length and the damage extent.

In this chapter, the assessment method and the information about the case study building were presented. Based on this information, the amount of the recovered wood sampled from the areas above was calculated. In addition, the results were compared with the results of the pre-assessment and the difference between the results and pre-assessment was discussed. After that, the cascading potential for recovered wood are investigated in the discussion part of the next chapter.

4 RESULT AND DISCUSSION

In this Chapter, the results of the calculation of the amount of wood in the case study building are presented first. Following this, all data from the demolition will be assessed and compared with the results from the pre-assessment.

4.1 Amount of wood in the case study building

From the information presented in Chapter 3, the amount of wood was calculated in each element. The whole calculation is attached as Appendix 2 (Amount of wood in element). To calculate the total amount accurately, more details of each element were generated and are shown in Figure 17.

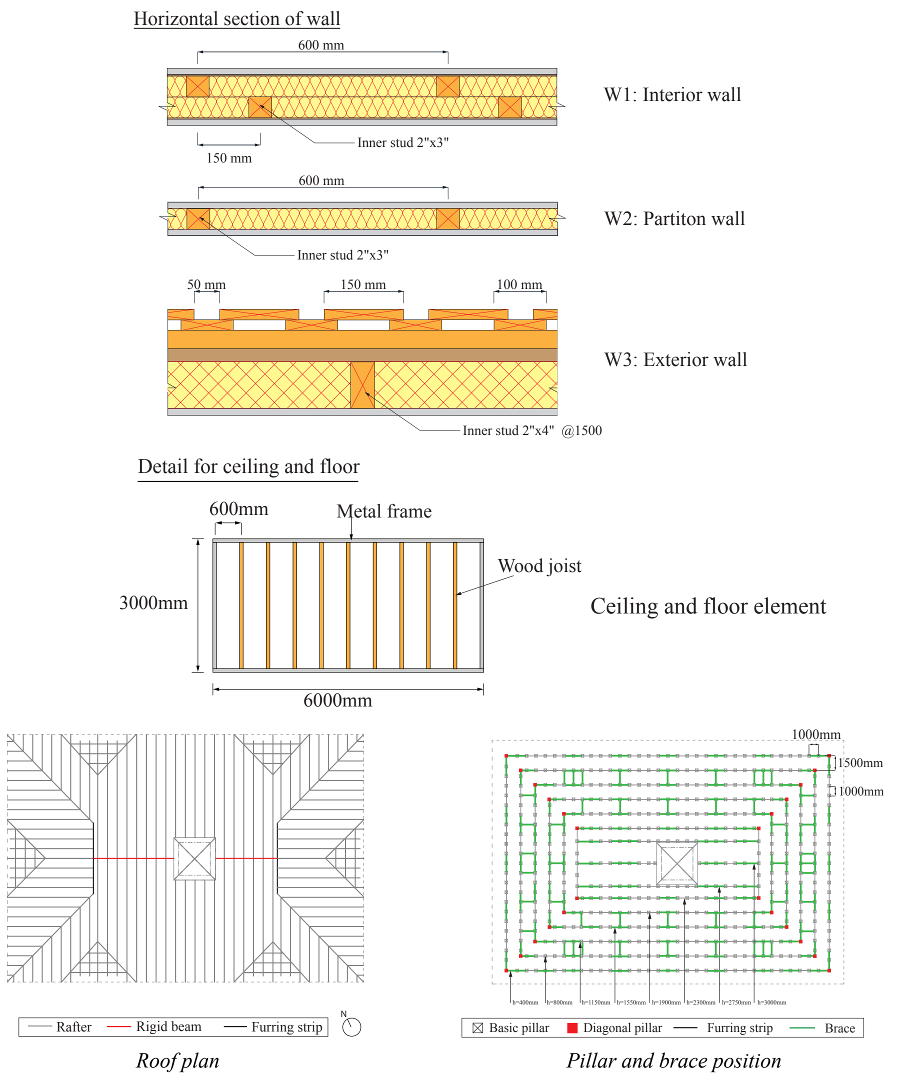

Figure 17. Detail of each element

The cross-section of each wood type was already measured in the detailed check and the length was individually measured from each drawing shown in the previous Chapter. The unknown lengths in some parts were estimated from the general length for the cross-section in the market. A summary of the amount of wood (the average length and number of each wood type) in each element is shown in Table 6. The average length was calculated for all the lengths of each wood type measured from the drawings. To observe the loss in the length due to demolition, the average length was compared to the length of the recovered wood randomly picked out after the demolition described in Section 4.2.6.

Table 6. Summary of the amount of each element

W1: Interior wall		
Cross section	Average length (mm)	Number
Stud 2"x3"	2851	223

W2: Partition wall		
Cross section	Average length (mm)	Number
Stud 2"x3"	2598	694

W3: Exterior wall		
Cross section	Average length (mm)	Number
Cladding 1"x4"	1434	2053
Cladding 1"x6"	1427	1490
Button 2"x2"	3195	195
Stud 2"x3"	3164	196

Floor		
Cross section	Average length (mm)	Number
Joist 2"x8"	3000	400

Ceiling		
Cross section	Average length (mm)	Number
Stud 2"x2"	6000	267
Joist 2"x8"	3000	400

Roof		
Cross section	Average length (mm)	Number
Roofing board and brace 1"x4"	2849	2792
Pillar 2"x4"	1349	526
Beam and rafter 2"x5"	4165	238
Beam 4"x4"	3595	151

4.1.1 Amount of wood in each element

From the calculation of wood used in the case study building, the amount of clean and painted wood by element is shown in Figure 18. From Figure 18, it can be understood that almost all of the elements contain clean wood except the exterior cladding. Considering the amount of wood in each element, the roof has the largest amount of wood (35.1 m^3). The exterior wall and ceiling follow (17.9 m^3 and 16.0 m^3 respectively). The total amount for whole building was 91.4 m^3.

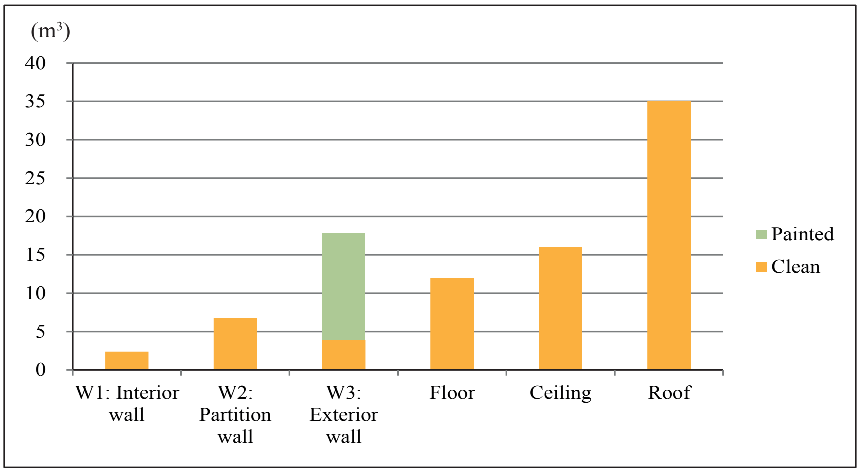

Figure 18. Wood amount in each element

4.1.2 Amount of wood in cross-section

Figure 19 shows the amount of wood in size. The 1”x4” and 2”x8” dimensions are used most. The clean 1”x4” is in the roof boarding and the painted 1”x4” is in the exterior cladding. The 2”x3” follows the 1”x4” and 2”x8”.

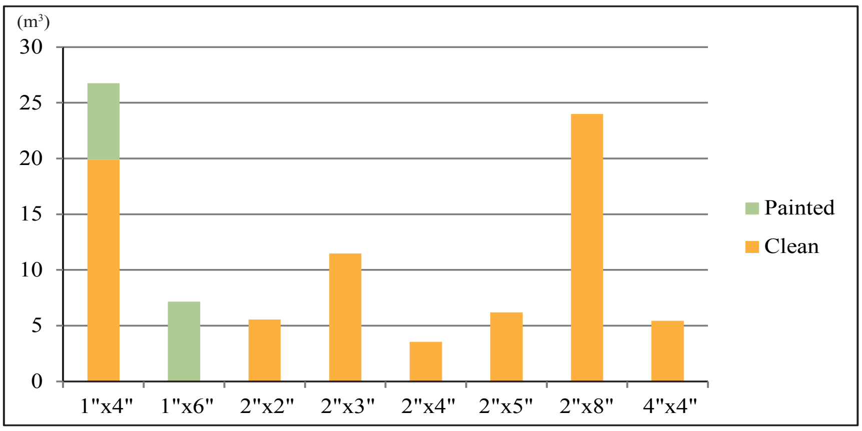

Figure 19. Wood amount in cross-section

4.1.3 Amount of wood in each element and cross-section

The amount of wood of each cross-section was also calculated for each element. From this result, the composition of the different cross-sections in each element can be observed. The result is shown as the amount of different sized wood in element (in Figure 20).

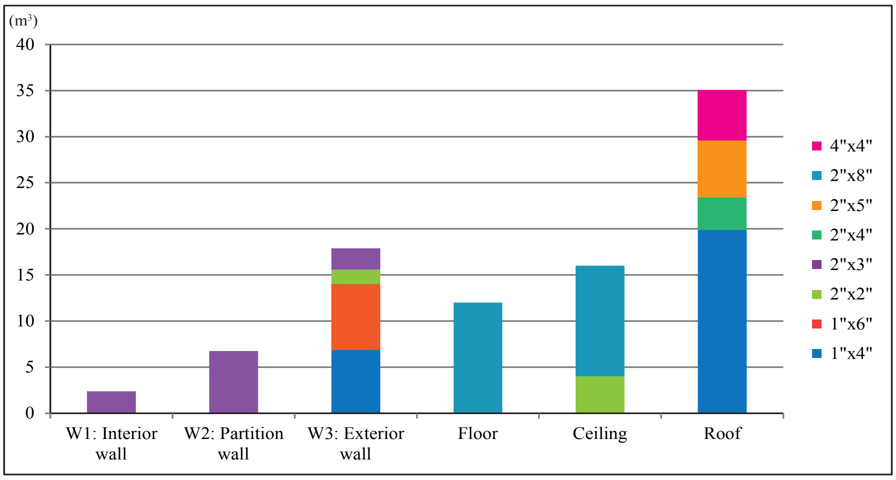

Figure 20. Wood amount in element and cross-section

4.1.4 Amount of wood in class

The wood amount was recalculated based on the cross-section class from the classification criteria to estimate the possible amount for cascading. Figure 21 shows the wood amount in class of cross-section.

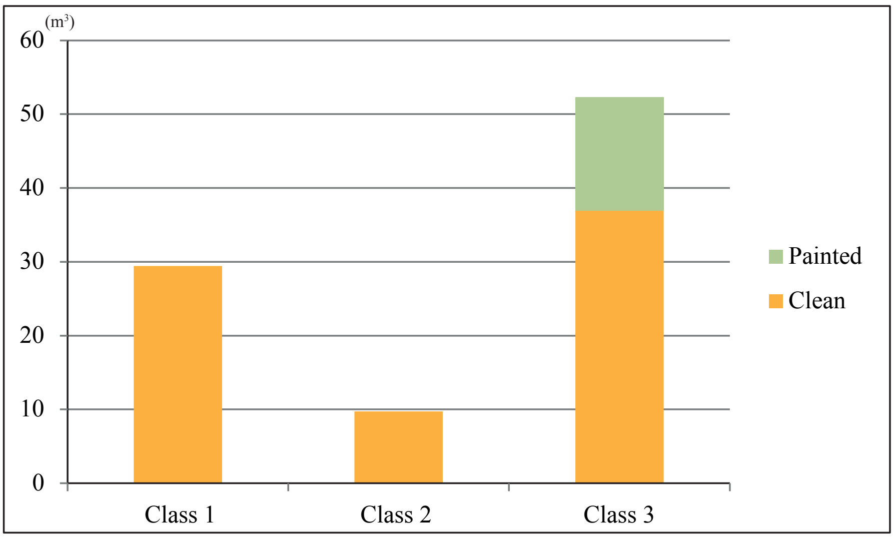

Figure 21. Wood amount in the class

4.2 Condition of wood after demolition

4.2.1 Demolition method and recovered condition

The demolition method was a combination of grabbing and crushing as seen in the pre-observation (Figure 22). First, the exterior cladding was grabbed separately from the exterior wall and the material from the roof part was ripped off and separated into different waste categories. After that, the exterior wall, interior wall, floor, and ceiling were crushed or grabbed as an element.

Figure 22. Demolition method for the case study building

Each recovered wood type was sampled from the piles according to the cross-section and the cleanliness, and the required information was measured. Examples of the recovered condition of each wood are shown in Figure 23.

Figure 23. Condition of wood recovered from the building

4.2.2 Amount of recovered wood from demolition

The data collected through demolition is listed from larger to smaller cross-section. The data includes the length, the number of nails and the condition of the recovered wood. The length, except for the broken edges or hugely damaged parts of each wood, was measured. The condition (o) means that wood is clean and the damage extent satisfy the criteria. If it does not satisfy the criteria, the condition is shown with (×). On the site, impregnated wood was strictly separated from other wood and was not included in the calculation either.

4.2.3 Class 1: Bigger cross-section from 2”×8” and 4”×4”

Tables 7a and 7b show the results of the 2”×8” and 4”×4” recovered wood. The length of the 2”×8” is random from 350 mm to 3000 (Original length). The length of the 4”×4” differs as well, but the average length is more than 3000 mm. Many of the lengths of the 4”×4” remained almost the same as the original.

Table 7a and 7b. Result of sampled wood from 2”×8”and 4”×4”

(a) 2”x8”			
No.	Length (mm)	Nail	Condition
1	1140	×	×
2	1210	×	×
3	860	×	×
4	3000	×	×
5	3000	×	×
6	700	×	×
7	1890	×	×
8	1680	×	×
9	2410	×	×
10	350	×	×
Ave.	1624	×	

(b) 4”x4”			
No.	Length (mm)	Nail	Condition
1	4120	5	o
2	4200	5	×
3	4695	6	×
4	1280	7	×
5	3520	4	o
6	3730	6	o
7	3100	5	×
8	3730	4	o
9	2500	6	o
10	2900	3	o
Ave.	3378	5.1	

4.2.4 Class 2: Middle cross-section from 2” ×4” and 2”×5”

Tables 8a and 8b show the results of the 2”×4” and 2”×5” recovered wood. The length of 2”×4” varies between 845 mm and 1620 (the longest length was originally 3000 mm). The length of the 2”×5” also varied between 1235 mm and 3100 mm. However, the 2”×5” was recovered in much longer lengths compared to the 2”×4”.

Table 8a and 8b. Result of sampled wood from 2”×4”and 2”×5”

(a) 2”x4”			
No.	Length (mm)	Nail	Condition
1	980	8	o
2	1235	4	×
3	1610	30	×
4	1555	26	×
5	1620	3	o
6	845	20	o
7	1565	3	o
8	900	11	o
9	1200	20	o
10	850	15	o
Ave.	1236	14	

(b) 2”x5”			
No.	Length (mm)	Nail	Condition
1	2650	8	o
2	1885	7	o
3	1235	10	o
4	2640	10	o
5	3100	18	o
6	2200	13	o
7	2100	12	o
8	2035	9	o
9	2400	5	o
10	1330	8	o
Ave.	2158	10	

4.2.5 Class 3: Smaller cross-section from 1”×4”-2”×3”

The results of the smaller cross-sections of recovered wood are shown in Tables 9a-e. The length of the 1”×4” and 1”×6” remained almost the same as the original and broken or cracked parts could not be observed. This means that the 1”×4” and 1”×6” did not lose length. The length of the 2”×2” and 2”×3” differed from less than 1000 mm to more than 3300 mm.

Table 9a-9e Result of sampled wood from 1” ×4”-2”×3”

(a) 1”x4”			
No.	Length (mm)	Nail	Condition
1	2220	1	o
2	3025	1.5	o
3	2695	1.5	o
4	3320	1.5	o
5	1450	2	o
6	3000	1	o
7	2350	1.5	o
8	2970	1	o
9	3955	1.5	o
10	3300	1	o
Ave.	2829	1.35	

(b) 1”x4” painted			
No.	Length (mm)	Nail	Condition
1	900	2	×
2	2350	2.5	×
3	1770	4	×
4	330	4	×
5	780	6	×
6	3080	2	×
7	1880	4	×
8	800	4	×
9	985	6	×
10	330	4	×
Ave.	1321	3.85	

(c) 1”x6” painted			
No.	Length (mm)	Nail	Condition
1	2245	2.5	×
2	790	2.5	×
3	2245	2.5	×
4	985	1.5	×
5	820	1.5	×
6	985	2	×
7	1900	2	×
8	985	2	×
9	2235	3	×
10	985	3	×
Ave.	1418	2.25	

(d) 2”x2”			
No.	Length (mm)	Nail	Condition
1	2830	3.5	o
2	3300	20	o
3	1675	15	o
4	1085	8	o
5	1100	10	o
6	1275	22	×
7	1855	12.5	o
8	2400	15	o
9	1000	13	o
10	1610	15	o
Ave.	1813	13.4	

(e) 2”x3”			
No.	Length (mm)	Nail	Condition
1	450	13	o
2	830	13	o
3	740	17	×
4	770	10	o
5	1370	10	o
6	1260	30	×
7	1390	10	o
8	1590	12	o
9	2385	13	o
10	2380	14	o
Ave.	1317	14.2	

4.2.6 Loss in length

The loss in length was calculated from the length of each lumber piece before and after demolition (Figure 24). Through the pre-assessment, the average length of each wood piece was calculated and the average length after the demolition was calculated from the recovered wood sampled. From a comparison, the effect of demolition on each wood dimension could be observed.

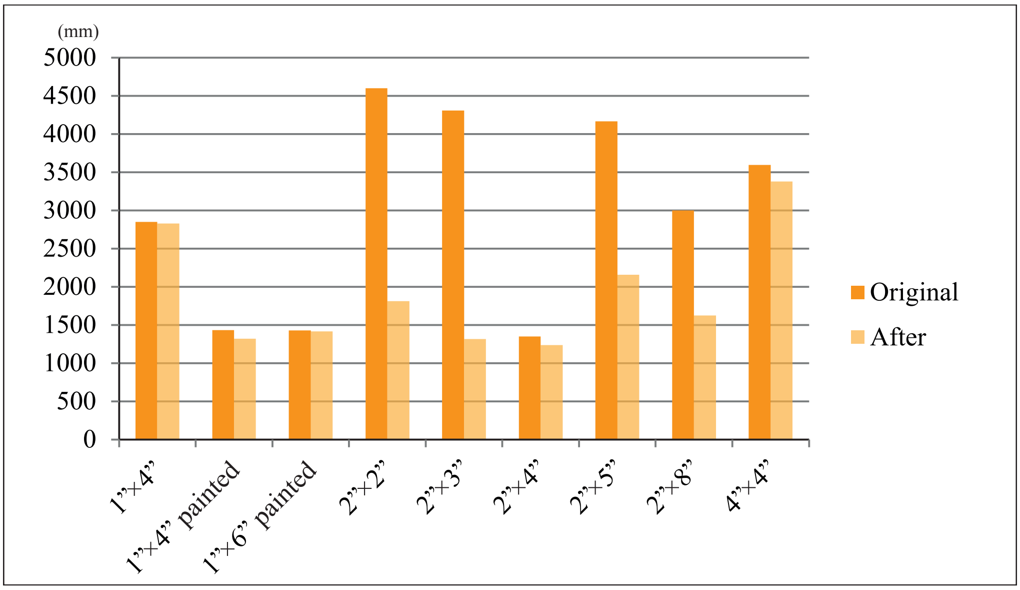

Figure 24. Loss in the length before and after demolition

Interesting features include the fact that the 1”×4” and 1”×6” over 90 % of the original length even though their cross-section is small. The similar tendency can be also seen in the 2”×4” and 4”×4”. The difference is that the length of the 2”×4” differed and most of the 2”×4” were broken.

In contrast, the 2”×2” and 2”×3” used in the wall or ceiling elements lost a lot of length (less than 40% of the original length remained). The loss is because they were grabbed by the machine as an element. The length of the 2”×5” and the 2”×8” are almost half the original.

After demolition, it was found that each cross-section exhibited different features irrespective of the class. Therefore, the contents after this section will be discussed for each cross-section.

4.3 Potential amount of recovered wood for cascading

Based on data of the wood recovered from the demolition, the percentage by quality was calculated for each cross-section dimension and also location used in the case study building, with a discussion about the length in this section.

4.3.1 Percentage of damage extent in cross-section

According to the criteria and the result from the assessment, the percentage of the damage extent in each cross-section was generated (Figures 25a-c). The potential for cascading can be seen from the quality defined by the damage.

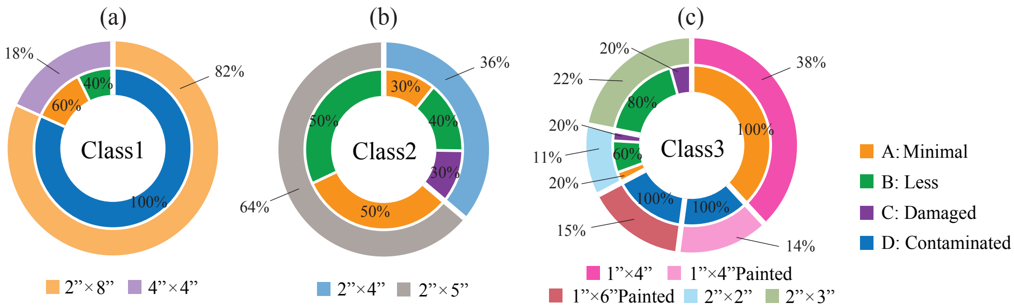

Figure 25a, 25b and 25c Percentage of quality of recovered wood in cross-section

All the 2”×8” belong to quality class D and this means that the 2”×8” is not suitable for cascading, while 60% of the 4”×4” belong to class A and 40% to class B (Figure 25a). From the size and the recovered condition, the 4”×4” has a lot of possibility for cascading. From 25b, the 2”×4” are almost evenly classified into class A, B and C. This result indicates that the condition of the 2”×4” is dependent on several factors. With regard to the 2”×5”, half of them belong to class A and the half to class B. The 2”×5” shows high possibility for cascading.

All the 1”×4” belong to class A, which shows the highest cascading possibility (Figure 25c). All of the 1”×4” and 1”×6” with paint belong to class D due to the paint and they cannot be utilized according to the criteria. 60 % of the 2”×2” belongs to class B, 20% to class A and 20 % to class C. 80 % of the 2”×3” belong to class B and 20% to class C. Based on the classification criteria, it can be considered that both the 2”×2” and 2”×3” have the possibility to be cascaded.

4.3.2 Percentage of damage extent in location

In the pre-assessment, the amount of wood was calculated in each element such as exterior wall, interior wall, partition wall, floor, ceiling and roof. It was understood that some of the same dimension wood was used in different elements. For instance, the 2”×2” were used as a button in the exterior walls and ceilings. The 2”×3” were used as the studs in the exterior, interior and partition walls (Figures 26a and 26b). The 2”×8” was used for the joists in the floor and ceiling elements.

Figure 26a. and 26b. Same dimensional lumbers used in different element

One problem during the classification of recovered wood on site was that it was not possible to detect the original location of the same cross-section wood used in a different location. The reason is that all kinds of wood were mixed up in the pile. Views of the different piles are shown in Figures 27a and 27b.

Figure 27a. and 27b. Different piles of recovered wood

To solve this problem, the location used for this analysis was determined as three different parts whose original location could be precisely found. The first and second parts were the independent parts consisting of the roof truss and cladding. The other is the unit part including the three different walls (except the exterior cladding), floor and ceiling elements in the building.

Using this location, the same data in Section 4.3.1 was analyzed by the location of the lumbers. The percentage by quality of recovered wood by location is shown in Figure 28.

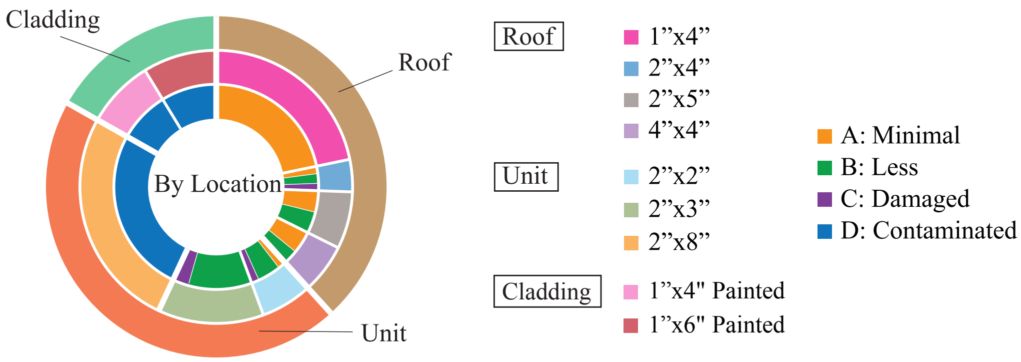

Figure 28. Percentage of quality of recovered wood in location

The general tendency in the independent parts such as the roof and cladding is that wood can be recovered in relatively longer lengths and with less damage. This can be seen particularly in the 1”×4”, 1”×6” , and 4”×4”. In the unit part, the recovered wood tends to be more damaged, which can clearly be seen in the 2”×2”, 2”×3” and 2”×8”.

One controversial issue can be found in the exterior cladding with the 1”×4” and 1”×6” dimension with paint because all of the 1”×4” and 1”×6” belong to class D due to the paint even though they can be recovered with minimal damage and also with almost the same length as the original. This aspect will be considered more carefully and the potential of the 1”×4” and 1”×6” with paint is discussed separately in Section 4.3.5.

4.3.3 Potential amount for cascading in cross-section

From the percentage calculated in Section 4.3.1 and 4.3.2, the potential amount for cascading in the whole building was estimated for each cross-section and is shown in Figure 29. The result obtained from this calculation could indicate the relevant targets regarding cross-sections for cascading in the case study building.

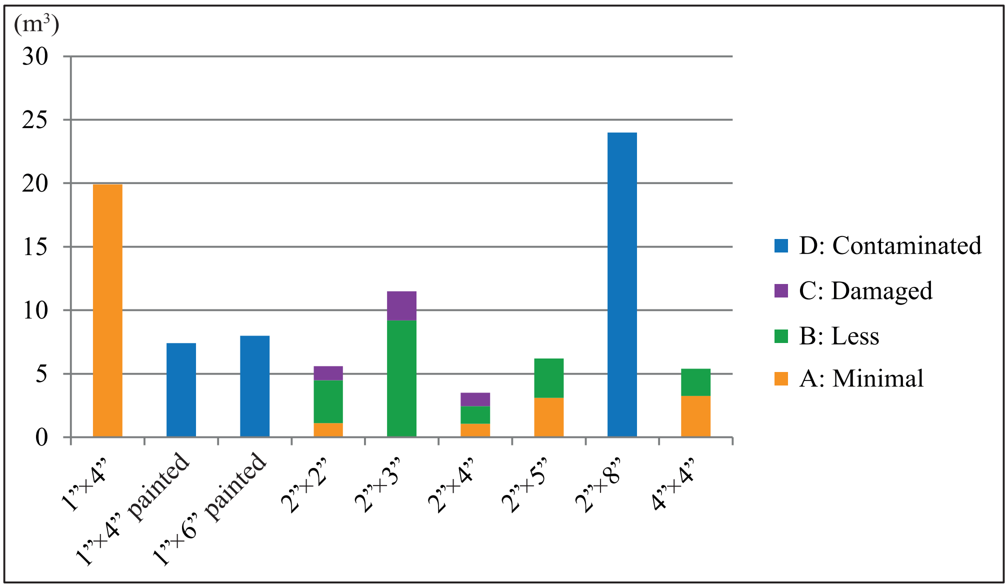

Figure 29. Potential amount for cascading in cross-section

From Figure 29, it can be understood that the 2”×8” (24 m^3) was the largest amount used in the case study building. However, that amount cannot be utilized because of the contaminated condition. On the other hand, the 1”×4” (20 m^3) could be recovered with minimal damage. Clean 1”×4” could be directly reused or reprocessed to other products. From this result, it can be said that the 1”×4” could be a good target for cascading. With respect to the 2”×3” (11.5 m^3) and the 2”×2” (5.6 m^3), the damage extent was relatively greater. According to the damage criteria, however, the 2”×2” and 2”×3” have the possibility for cascading. Regarding the damage extent to the 2”×4”, the behavior was similar to the 2”×2”, but the 2”×4” could be a good target because the 2”×4” was used in the independent parts such as roof pilar and the cross-section is larger than the 2”×2”.

The 2”×5” and 4”×4” were similar each other (the amount was about 6 m^3 and 5 m^3 respectively). The extent of damage to these dimensions indicates the potential for cascading, particularly by reprocessing as structural components. In case the first step of cascading is reuse, more cascading steps could be expected. Therefore, the 2”×5” and 4”×4” can be considered to be good targets for cascading even though the amount is small in the building. Regarding the 1”×4” and 1”×6” with paint (7.4 m^3 and 8.0 m^3) used in the exterior cladding, they are classified into class D due to surface paint as discussed in the previous sections.

4.3.4 Potential amount for cascading in location

Following the potential amount in cross-section, the potential amount in location was also calculated (Figure 30).

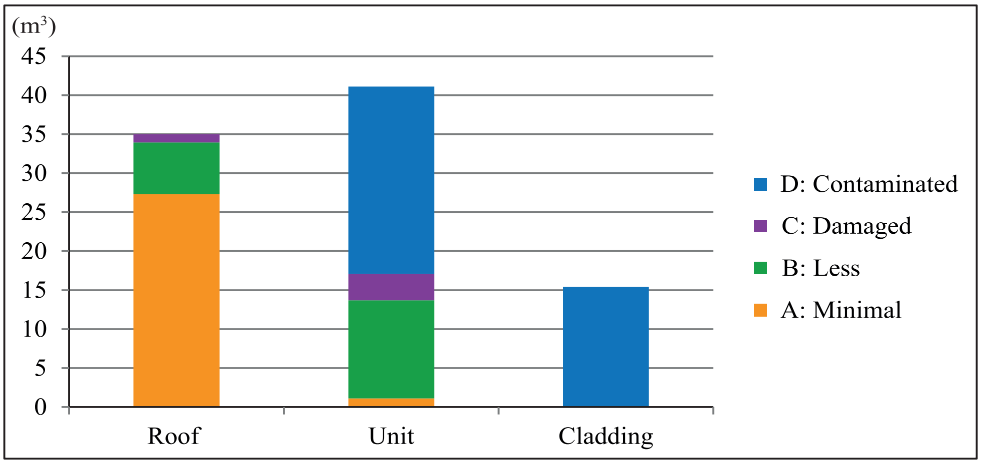

Figure 30. Potential amount for cascading in location

As can be seen in Figure 30, a large amount of wood in the roof part can be cascaded. This is mainly because wood in the roof part was independently used so that it could be recovered with less damage. The damage in the roof part was mainly caused by the joint and grabbing by the machine. It was observed that the wood tended to be more damaged in the case that it was jointed with a lot of parts. With regard to the cladding part, the potential amount is almost none, which is a result of the paint on the surface.

In the unit part, the potential amount for cascading is much less. The reason for this is that the 2”×8” accounts for the largest amount in the unit, but all of them belong to class D. In addition, the unit was demolished as an element because a lot of materials such as insulation and board products were attached and it was difficult to separate them. Therefore, the potential amount of the unit part is decreased due to these factors even though the total amount was the greatest.

In the previous sections, the results have been analyzed separately by cross-section and the location of recovery. However, the cascading potential for recovered wood should be discussed in light of both cross-section and location.

In addition, technical aspects such as building design and demolition method are also concerned with the potential. Therefore, the cascading potential of the case study building will be discussed from both the cross-section and location point of view as well as the technical issues in Section 4.4.

4.3.5 Potential of 1”×4” and 1”×6” with paint

Considering the condition of recovered 1”×4” and 1”×6” with paint, they surely have potential for cascading provided the paint is not hazardous. In the case of the case study, the paint for the exterior cladding seemed a general paint and it was painted only on the surface as seen in Figures 31a and 31b even though the details of the paint should be confirmed by a future study.

Figure 31a and 31b. Condition of exrerior cladding from the case study building

As one example regarding the potential for cascading exterior cladding, Janowiak et al (2005) investigated the feasibility of cascading of Douglas-fir exterior cladding with lead-based paint (130×19mm) recovered from US military buildings. They stated that about 75% of recovered cladding could be cascaded to valuable secondary products particularly as Tongue and Groove flooring. The potential profit for the T&G flooring was 3 to 6 dollars per square foot according to their calculation.

Based on the results from the research by Janowiak et al (2005), it can be considered that the 1”×4” and 1”×6” with paint from the exterior cladding in the case study building will also have the potential for cascading and it is worth investigating the potential in other buildings.

4.4 Cascading potential of recovered wood

4.4.1 Cascading potential and improvements

Recovered wood can be cascaded in different ways. Figure 32 shows an ideal cascading flow. The more cascading steps it takes, the longer wood can store carbon and save virgin resource, which results in the advantages given by cascading.

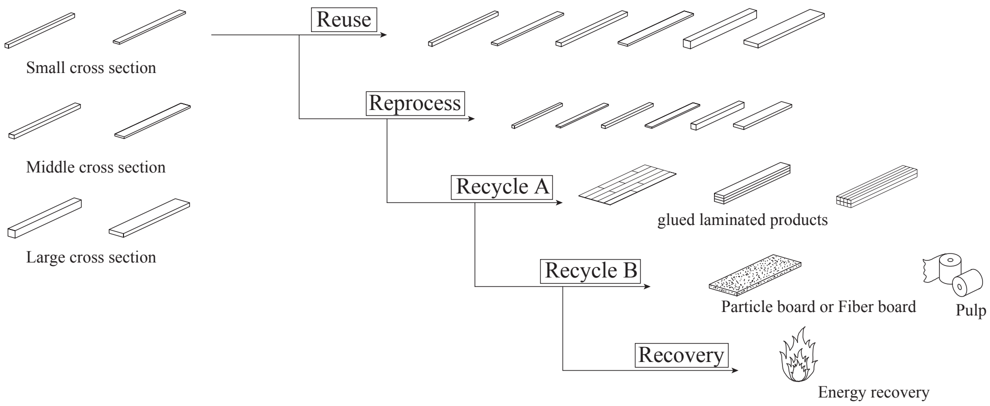

Figure 32. Ideal cascading flow

Exterior cladding and roofing board: 1”×4” and 1”×6”

The 1”×4” and 1”×6” with paint are also included in this category. The possible cascading flow for the recovered 1”×4” and 1”×6” is shown in Figure 33. The 1” ×4” and 1” ×6” can be cascaded with many steps. At first, it can be directly reused as exterior cladding in a new building. Or a more realistic flow could be reprocessing them to scrape the surface paint and then used for boarding again.

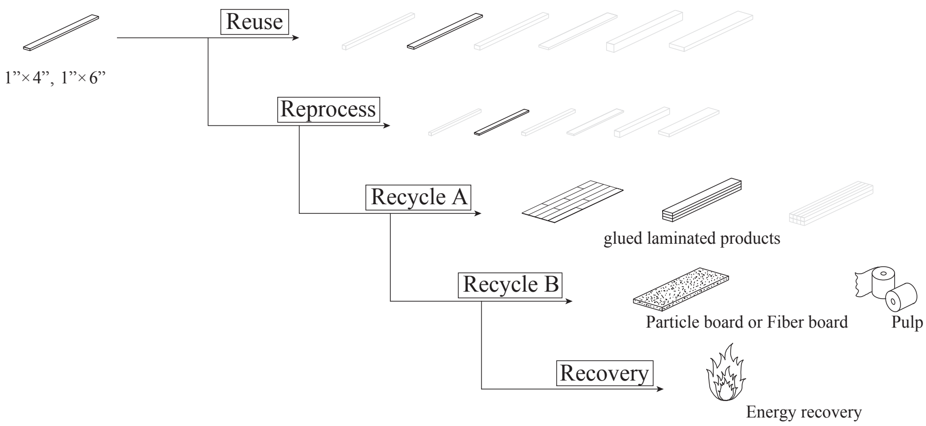

Figure 33. Ideal cascading flow for 1”×4” and 1”×6”

Reprocessing could expand the availability of the 1”×4” and 1”×6” in different building types and board products. The cladding could be recycled as a resource for laminated products as well.

With respect to improvements in the potential for the 1”×4” and 1”×6”, if that the cladding is ripped of more carefully, all of them could basically be recovered in the original condition. In this sense, the current demolition method with a bit more care, is reasonable for recovering of the 1”×4” and 1”×6” for cascading.

However, there is an issue with the 1”×4” used as a roof brace and furring strip (Figure 34). It was easily broken into smaller pieces from the grabbed part when it was roughly grabbed out of the roof pillar. This is mainly because both edges of the brace were attached to the pilar with nails and it caused breakage in the grabbed part.

Figure 34. 1”×4” brace and furring strip in roof part

To recover the 1”×4” used in a brace or furring strip in better condition, the joint needs to be improved. If the joined is designed for easy detachment, the 1”×4”could be grabbed and recovered in good condition. The improvements in the joint system will be discussed further in the next section. Issues regarding the joints discussed in the next section are also applicable to other cross-section such as the 2”×4”, 2”×5” and 4”×4”.

Improvement in joint design

The joint system is critical for cascading, particularly for wood in the roof parts. By improving the joint, damage by demolition could be minimized and the cascading potential could be also enhanced. The joint in the case study building and possible existing solutions are shown in Figure 35.

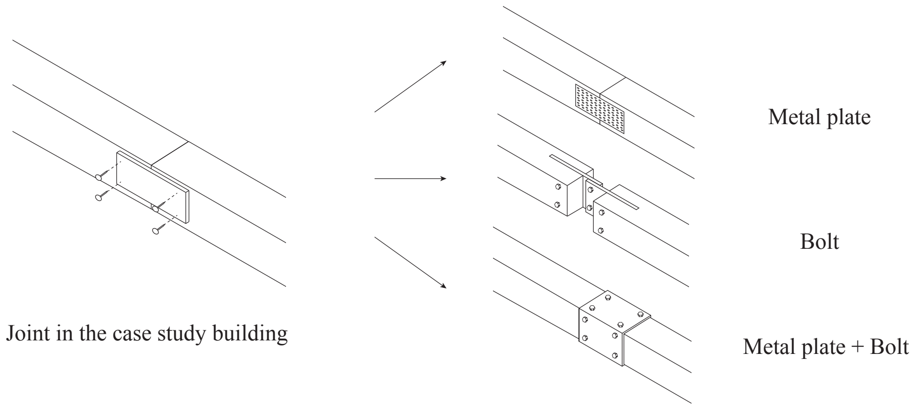

Figure 35. Possible options for joint

There are a variety of solutions for joints in the market already. There are suitable situations for each joint so that it is necessary for the designer to pay more careful attention to choosing the appropriate joint for their design.

In Japanese historical buildings, Shiguchi or Tsugite (wood joints) have been used (Figure 36). They could be developed with the existing solutions above to create new joints more suitable for cascading.

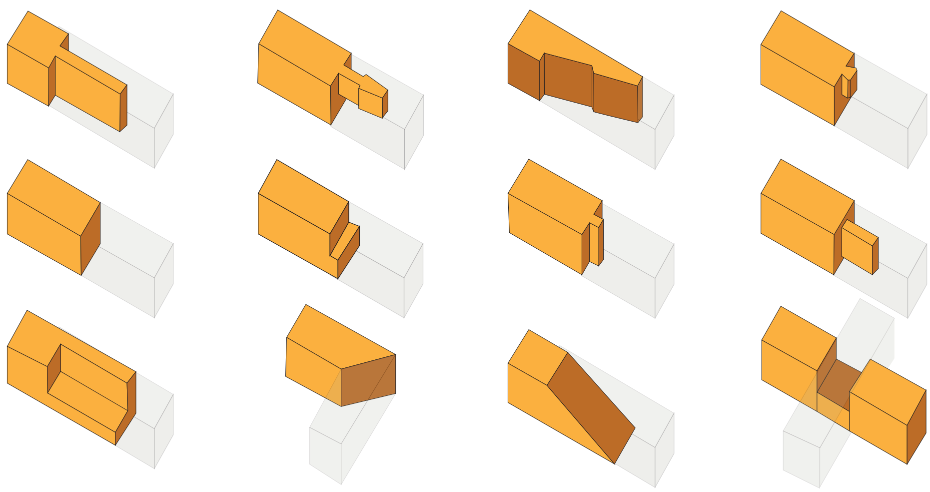

Figure 36. Japanese traditional wood joint (Regenerated from Mokujyuken,2010)

This historical joint system could be reconsidered in a modern context. As long as it does not cause damage and is easy to disassemble, the wood joint could be combined with screws or metal bolts. This kind of hybrid joint system would be suitable especially for prefabricated or industrialized buildings.

In the case that the joint system is standardized, it would be easier to adopt the system to different types of buildings and suitable demolition methods for a building with that system could be considered at the same time. This could enhance the cascading potential and the efficiency of the demolition process, which would be profitable for the industry. For this purposes, the applicable and appropriate joint design for cascading needs to be further developed.

Exterior button and wall stud: 2”×2” and 2”×3”

The possible cascading flow for recovered 2”×2” and 2”×3” is shown in Figure 37. Considering the recovered condition, the 2”×2” and 2”×3” dimensions are not suitable for reuse or reprocessing since the cross-section is not large enough.

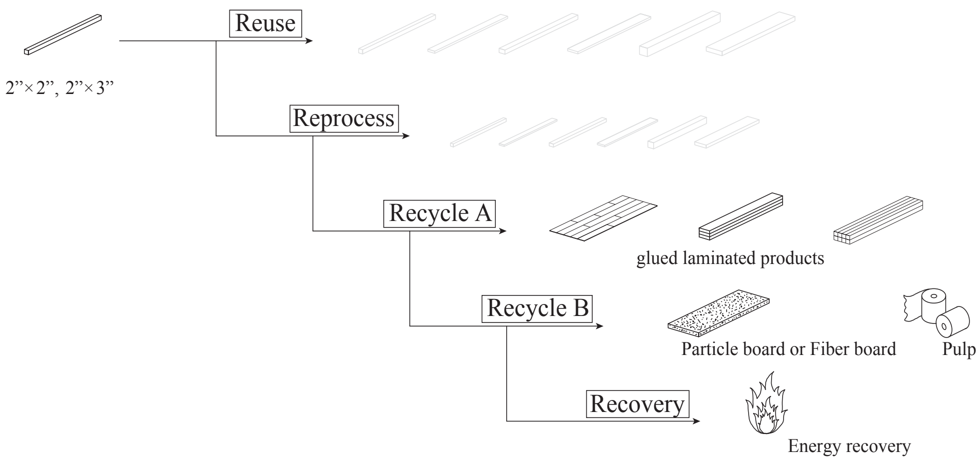

Figure 37. Ideal cascading flow for 2”×4” and 2”×6”

The most valuable and possible secondary products for the recovered 2”×2” and 2”×3” are laminated products such as smaller dimensional CLT or glulam. The recovered 2”×2” and 2”×3” could be used in the core part of glue laminated products. The core part would be sandwiched by a surface layer of virgin wood.

Floor parquet could be one of the possibilities as well. Since the parquet does not require bulky thickness, the 2”×2” and 2”×3” can be sawn and glued together. If recovered wood is more than these cross-sections at least, it could basically be utilized in laminated products. The cascading potential for the 2”×2” and 2”×3” dimensions has to be more carefully investigated further, however, because it requires more effort to recover it from the element and remove the attached materials, even during the sampling. This extra effort will result in more cost and time, which will be a disadvantage.

Regarding improvements, the 2”×2” and 2”×3” dimensions also have the potential for cascading even though the recovered length became much shorter than the original length and their cross-section is not so large. The most problematic factor for the 2”×2” and 2”×3” is that they were attached to other materials (Figure 38a). This also required more effort to remove all attached materials (Figure 38b).

Figure 38a and 38b. View of 2”×3” in element and required effort to remove

The problem with the 2”×2” and 2”×3” is due to mainly the building design rather than the demolition method. If they could be easily removed from the element separately, the demolition and separation of the materials would also be easier and more efficient. This is a common problem for a unit part which has a lot of attached materials and the problem can commonly be seen in prefabricated or industrialized building of different ages.

The main problem is that the prefabricated element is generally designed for efficient assembly in the factory. But the disassembling process is not taken into account at all, which causes difficulty in the demolition process and the material separation process when recovered wood is cascaded.

To utilize the 2”×2” and 2”×3” for reuse or reprocessing, it needs to be recovered in almost the original condition, which is still challenging for machine demolition and with current building design. Even if the element is carefully demolished, the separation of different attached materials still requires a lot of work.

To cascade the 2”×2” and 2”×3” dimensions, it might be better to develop element and modular design rather than changing the demolition method. One idea is that the element design or modular design system could be developed to enable buildings to be cascaded as an unit, if it is difficult to separate each material.

Element and modular design for cascading

Considering existing buildings, it is also challenging to reuse the elements, even partially. Moreover, demolition of the unit part is also problematic because the separation of different materials requires a lot of effort. To enhance cascading, modular design or element design could be improved to suit cascading building materials more. Figure 39 shows the basic concept.

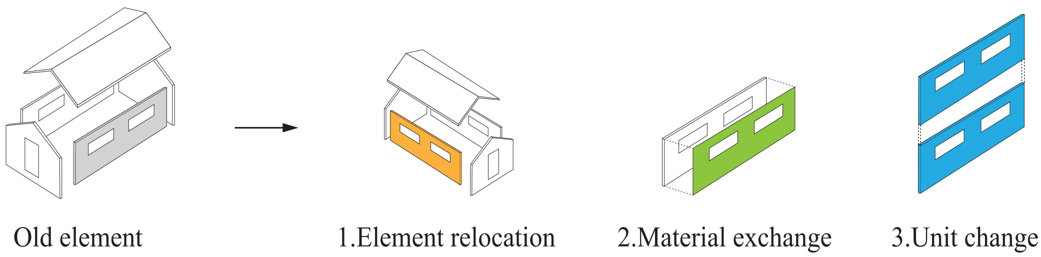

Figure 39. Concept diagram for deisgn at building level

In the case that the condition of the element is satisfactory, it could be relocated to a new building directly (option 1). It could also be expected that some materials in the element need to be changed (option 2) or some parts need to be reprocessed for the design of a new building (option 3). In those cases, it could be brought to the factory and the necessary adjustments could be done and the adjusted element could be transferred to a new building. In Finland, many buildings are prefabricated irrespective of scales or uses, so that these types of idea for building design has potential for the future.

Roof pillar: 2”×4”

The possible cascading flow for recovered 2”×4” is shown in Figure 40. The recovered condition of the 2”×4” was not sufficient for the direct reuse. However, it could be reprocessed to lumber with smaller cross-section or cascaded as laminated products. The 2”×4” is a basic size in construction and it has been used in different parts in the building. Therefore, it will be even more beneficial to discuss improvements for the enhancement of the cascading potential.

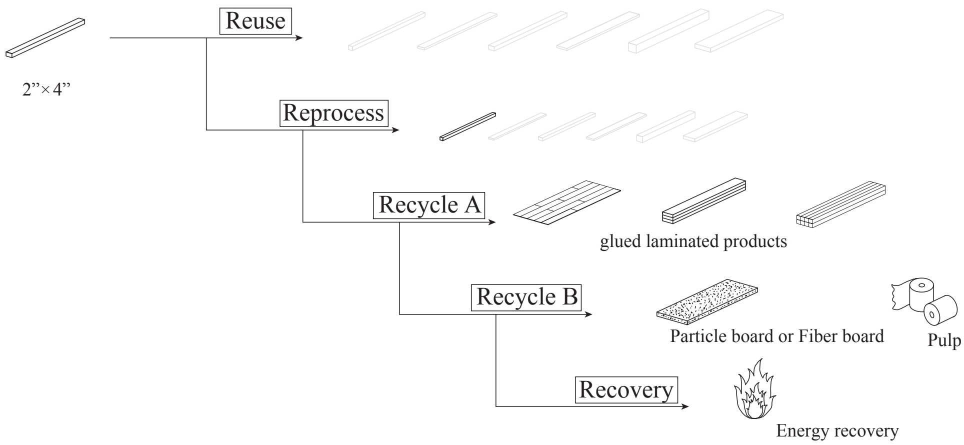

Figure 40. Ideal cascading flow for 2”×4”

With respect to the improvements, the original length of the 2”×4” roof pilar varied from 400 to 3000 mm. According to the on site monitoring, the longer the 2”×4” (particularly over 1500 mm) was, the more easily it was broken when it was grabbed and taken out from the roof part by the machine.

Figure 41 shows the condition after grabbing. The broken pillar can be seen in the figure. This breakage was caused by the effect from both the building design and the demolition method. The first problem is in the joint as discussed in the 1”×4” brace. Another problem was in the rough grabbing and pulling by the demolition machine. To avoid the problem, the pilar needs to be more easily detached from the other parts by an improved joint system. In addition, the machine should grab the area near the edge since the longer pillars tended to be broken in the middle part when it was grabbed.

Figure 41. View of 2”×4” and 2”×5” in roof

The joint could be designed for easy dismantling using the system discussed in “*Improvement in joint design”*. With that system, the demolition could be effective and the condition of the recovered 2”×4” could also be extensively enhanced.

Roof rafter: 2”×5”

The potential cascading flow for the recovered 2”×5” is shown in Figure 42. As seen in the recovered 2”×4”, a similar possibility can be proposed for the 2”×5”. The recovered 2”×5” is larger in cross-section so that it could be reprocessed to a variety of smaller lumbers. In addition, with respect to the recovered 2”×5” could also provide more options for different laminated products. About improvements in the 2”×5”, it was used as a roof rafter as can also be seen in Figure 41. Similar to the case of the 2”×4”, damage to the 2”×5” was caused mainly at the joint with the pillar, which also indicates the necessity for the developing the joint. By improving the joint and more careful grabbing, the cascading potential could be even higher.

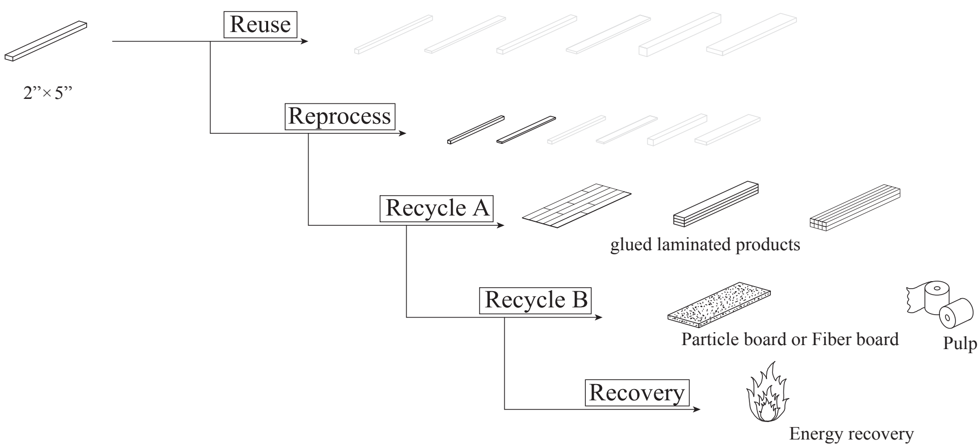

Figure 42. Ideal cascading flow for 2”×5”

Joist in floor and ceiling: 2”×8”

The potential cascading flow for recovered the 2”×8” is shown in Figure 43. The potential of the 2”×8” in the case study building is much lower even though the cross-section is large enough for direct reuse or reprocessing.

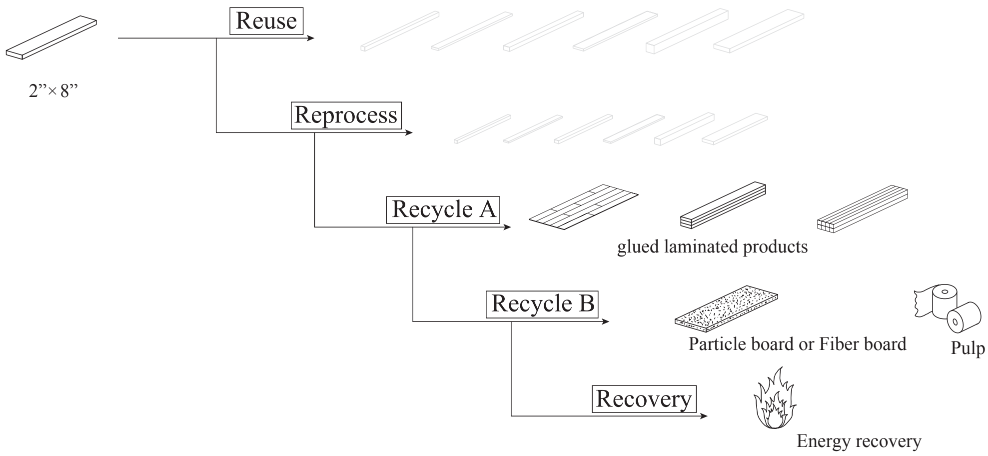

Figure 43. Ideal cascading flow for 2”×8”

The recovered 2”×8” has the possibility for laminated products. However, it may require more effort to recover the 2”×8” since it needs to be taken out from the element and other materials are still strongly attached. To avoid this extra load, the building design should be reconsidered and a new design such as that discussed in “*Element and modular design for cascading*” should be applied.

Similar to the recovered 2”×2” and 2”×3” wood pieces in the unit part, the problem is attached materials, such as insulation and tape as can be seen in Figure 44. These is also a common problem in the unit part and needs to be considered at the primary design stage by the designers.

Figure 44. View of 2”×8” in element and the tape attached

About the damage, it was caused when it was grabbed as an element and in separating it from the metal frame. Most of the loss in length was also caused during this process. This demolition should be more “gentle” if the cascading potential is to be enhanced. However, the insulation is still attached to the 2”×8” with tape even if it is recovered in longer lengths, which decrease the potential.

To enhance the potential, the insulation should not be attached to the wood. One solution is to use sheet type insulation and not attach it directly to the wood. This is a small improvement, but it could raise the cascading potential, to which designer should pay more attention when designing the building. A second idea is intentionally use impregnated wood joists to avoid using water proof tape. As long as the impregnated joist is recovered in good condition, it can be reused in a new building. Another idea is to apply the concept from “*Element and modular design for cascading”* to the 2”×8”.

Roof beam: 4”×4”

The potential cascading flow for recovered 4”×4” is shown in Figure 45.

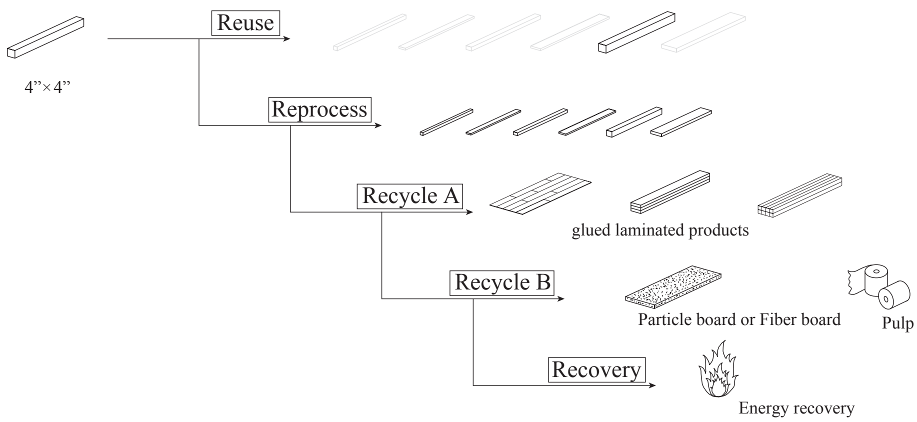

Figure 45. Ideal cascading flow for 4”×4”

According to the condition of the recovered 4”×4”, it has the most cascading potential of all wood used in the case study building. The recovered 4”×4” with fewer cracks could be directly reused as structural members in a new building after all the nails had been removed. The 4”×4” with longer cracks could be reprocessed and cascaded as smaller lumber for stud or boarding in a new building.

The recovered 4”×4” could surely be utilized for laminated products as well. It still requires the removed all of nails or attached metal plates from the recovered 4”×4”, but it is worth cascading. Thanks to the reasonable recovered condition, the cascading flow is ideal for recovered wood from buildings in general.

During the demolition, the 4”×4” could be recovered in reasonable condition and with almost the original length, which leads to high cascading potential. However, there are still some issues upon to be improved to enhance the potential of the 4”×4” even more.

Only one threat to the 4”×4” pillar are the cracks caused by drying or bigger nails (Figures 46a and 46b). These bigger nails could be found only in the recovered 4”×4” wood pieces. The cracks caused by drying and bigger nails were long in some wood pieces even though the depth was less than 10mm. The crack depth seemed not critical, however the structural property should be investigated in future research, particularly for the purpose of reuse as a structural member.

For the enhancement of the cascading potential, the damage caused by the joint part can be considered to be the target for improvement. The same solution as in the joint between the 2”×4” pillar and the 2”×5” rafter can be applicable to the 4”×4” as well. Even though it is difficult to avoid natural drying cracks, crack caused by bigger nails can be avoided by not using that type of nail, and the cracks can also be reduced by an improvement in the joint system discussed already.

Figure 46a and 46b. View of 4”×4” in roof and the nails and crack

4.4.2 Extension of target for cascading recovered wood

Another interesting perspective could be observed from the statistics provided by Kuusakoski Oy. Figure 47 shows the percentage of waste from different single family wooden houses in Finland. No.1-15 are wooden structure houses with wood exterior cladding. B1-3 are wooden structures with a brick exterior.

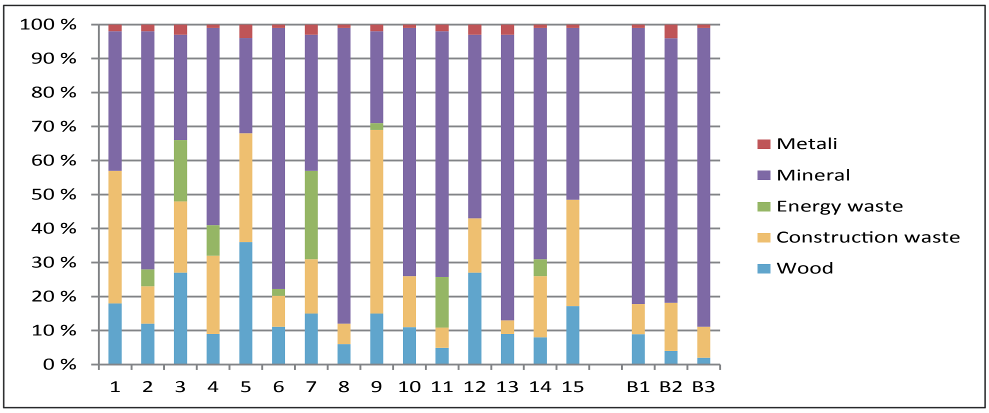

Figure 47. Waste percentage of single wooden family house (provided by Kuusakoski Oy)

The figure shows that the average percentage of wood waste in the buildings with wood exterior cladding is much higher (15%) than that of buildings with a brick exterior (5%). This indicates that wood cladding is one of the major sources in wood waste categories and can be utilized to raise the cascading potential. In addition, recovering exterior cladding does not require special skills and the process can be done by a general demolition machine, which indicates that exterior cladding could already be utilized.

Moreover, wood cladding has also been used for other types of buildings such as concrete and steel structure buildings. Considering this aspect, the target for the cascading of recovered wood can be expanded even further. To make the best use of painted exterior cladding, the classification criteria needs to be developed and feasible and competitive applications for the Finnish market need to be discussed separately. Other wood products such as wood interior finishing or wood flooring could be also good targets for cascading. These potential products need to be further explored with more, and different, case studies in future research.

4.5 Other factors

In addition to the topics discussed in the previous section, other factors need to be investigated from a different point of view for the facilitation of cascading wood from buildings. The factors discussed in this section are classified into 4 categories: technological, environmental, economic and social aspects.

4.5.1 Technological aspect

Suitable demolition method

Previous studies by Miyazaki et al (2003) and Hradil (2014) provides comparative data for the duration and recovery rate, shown Table 10. The term “deconstruction” generally means a method which aims to recover as many construction materials as possible for new applications (Chini and Bruening, 2003). Demolition places generally more priority not on recovery, but on time efficiency.

Table 10. Required time for different types of demolition
(generated from Miyazaki et al, 2003, p.87 and Hradil, 2014, p.30)

Resource	Miyazaki et al, 2003, p.87		Hradil, 2014, p.30		
Method	1. Dismantling	2. Demolition	3. Demolition A	4. Demolition B	5. Deconstruction
Description	All parts are carefully dismantled by hand	Inner part is dismanteled by hand and structural part is demolished by machine	All parts are demolished by machine	Inner part is dismanteled by hand and structural part is demolished by machine	All parts are carefully dismantled by hand and nails, connecters are removed and cleaned
Duration	142 [1)]	26	About 1 day [2)]	3-6 days	6-12 days

1) The number is calculated as people x hour / m^2

2) The result by Hradil (2014) indicates the general required time for single family house by different methods. This is examples and not comparative for the result of the studied building.

The comparison clearly shows that deconstruction takes much more time compared to the duration of demolition. Due to the time required, the cost of deconstruction will naturally be higher. Considering the time required and the extra cost, it can be said that deconstruction is not necessarily suitable method, for cascading.

Following the duration, the percentage for cascading potential by different methods is shown in Figure 48. The numbering in the graph correspond with that shown in Table 10.

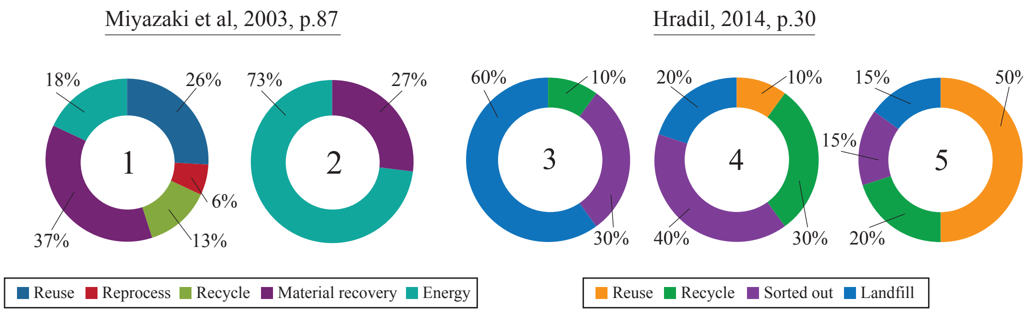

Figure 48. Percentage by different demoliton method
(generated from Miyazaki et al, 2003, p.87 and Hradil, 2014, p.30)

From Figure 48, it can be seen that the cascading potential, such as the reuse and reprocessing of recovered wood is much higher in almost all cases in deconstruction (No.1, 4 and 5). On the other hand, the cascading potential by demolition is relatively lower (No.2 and 3). These results indicate that there is the possibility of profit to hedge the extra cost of cascading wood to valuable secondary products.

It also can be said that a suitable demolition method needs to be considered with the best balance of the duration during the demolition process as well as the profit from the sales of wood recovered from building. Furthermore, a balanced method for the Finnish situation should be determined with other factors such as more accurate cost comparisons and an environmental assessment discussed in the next Sections.

Classification for cascading

For this research, the classification criteria was defined in Chapter 3. These criteria are based on existing classification systems in different countries. Classification on the site was carried out in terms of the cleanliness, the cross-section and the damage extent of the recovered wood. From the results, it can be mentioned that the cascading potential can be observed by classifying recovered wood according to the cross-section and the damage.

However, there are still controversial issues about the classification by the cleanliness as painted 1”×4” and 1”×6”. Even if wood is painted, the wood can be cascaded unless the damage extent is high and the paint is hazardous. This highlights that hazardous material is more critical for cascading. Based on these results, a suitable classification system for cascading should also be developed with more case studies.

Evaluation, certification and labelling system

To facilitate the cascading of recovered wood, an evaluation of recovered wood is crucial particularly for cascading wood for structural purposes. In addition to the evaluation, certification and labelling also take important roles for the facilitation of cascading. For instance, a variety of existing models can be seen in the paper industry, so that a suitable system for cascading should be further investigated.

4.5.2 Environmental aspect

Necessity of life cycle assessment including whole process

The different environmental benefits of using recovered wood have been widely examined through an investigation of previous studies in Chapter 2. The environmental benefits from the cascading of recovered wood are as follows.

- Resource for secondary products and energy recovery
- Energy saving in manufacturing process
- Carbon storage capacity and reduction of carbon emission
- Reduction of C&DW waste

In almost all cases, it is reported that using wood products and recovered wood in buildings are environmentally profitable. However, the environmental benefits from cascading of recovered wood have to be investigated more carefully.

For example, the impact caused by demolition and transportation processes can be critical for cascading from the environmental point of view, if the duration of demolition and the distance of transportation becomes longer. To discuss the feasibility of cascading of recovered wood, the environmental impact of the whole cascading process needs to be taken into account as a future topic.

4.5.3 Economic aspect

Accurate cost comparison

The cost comparison of deconstruction and demolition for several typical single wood houses were investigated in the United States by Guy (2003) and in Japan by Miyazaki et al (2003). The comparison is shown in Table 11.

Table 11. Cost comparison of deconstruction and demolition including recovery benefit (modifierd from Guy, 2003, p.18 and Miyazaki et al, 2003, p88)

Guy, 2003						Source	Miyazaki et al ,2003	
1	2	3	4	5	6	Building	A	B
2014 sf[1]	1436 sf	2059 sf	1238 sf	992 sf	1118 sf	Area	$67m^2$	$84m^2$
5.68[3]	4.93	4.78	4.29	4.54	7.91	Demolition[2]		9,774
6.21	5.01	5.58	7.63	5.05	9.34	Deconstruction[2]	10,269	
4.67	0.39	2.81	3.73	4.65	3.42	Recovery[2]	2,268	143
4.14[4]	0.31	2.01	0.39	4.14	1.99	Total	8001	9631

1) sf = square feet 2) Demolition, deconstruction, recovery = cost in each catefory 3) $ / sf in guy´s case, ¥/ m^2 in Miyazaki case
4) Total in guy´s research shows the difference of the cost calculated as Demolition cost - Total deconstruction cost (deconstruction - recovery)

In the comparison by Guy (2003), the costs for labor, equipment, asbestos and lead handling, disposal are included. The benefit from recovery is calculated to be 25-50% of the local price of new lumber. In the calculation by Miyazaki (2003), basically the same variables are calculated but the benefit is calculated by (the average sales price) - (the manufacturing cost). The result clearly shows the predominance of deconstruction with the recovery of wood. In fact in the current situation, however, deconstruction is not a major method for demolition in the construction sector. If it is profitable, the industry should already have applied the method. This means that more accurate cost comparison needs to be conducted and more factors regarding cascading should be analyzed for the business feasibility with a possible business model, in future research.

4.5.4 Political aspect

Recycling fee, incentive and tax reduction system

The electronics waste recycling fee in the US, the EU, and Canada is widely known to be one of the effective recycling fees. This fee is collected on purchase and is used to handle the recycling of electronic devices. This fee encourages stakeholders to recycle devices rather than dispose of them. There are also a variety of incentives and taxation systems in the world. An ecological taxation system could be a relevant example as a model policy. It could be beneficial to extend this sort of incentive system to manage recovered wood including sustainable demolition process.

***Social acceptance* and toward environmentally friendly society**

Social acceptance is one of the key drivers for cascading. It should be encouraged by a combination of other aspects though. Looking back in history, recycling paper, electric devices or vehicles were not necessarily common. It also required effort and took time to facilitate them in order to be accepted in society.

With respect to recovering materials from buildings, it has been widely seen in the world. As an example, traditional log houses used to be commonly reused for new log buildings in Finland. Similar patterns can be observed in Japanese traditional post and beam timber building. They were dismantled piece by piece and reused in new buildings. Another historical example in the UK is London's crystal palace of 1851, which was built and dismantled in one place and then reused in other place (Crowther, 2005.)

For reuse, details of buildings must be specially designed to be reused. Utilizing historical experiences in a modern context could be completely profitable. The utilization might also result in historical benefits in terms of the preservation of local architecture and tradition in society (Chini and bruening, 2003).

The other factors discussed in this Section could be considered with a combination of them for the facilitation of cascading. For instance, political strategies could easily combine and support different strategies from the technological, environmental and economic point of views. This also means that it could be beneficial to establish strategies that facilitate cascading by several aspects.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The purpose of this study was to investigate the potential for cascading wood from buildings. The potential amount for cascading was calculated before and after the demolition and the calculated data was compared. Finally, the results were assessed with the potential amount available for cascading discussed in terms of different perspectives such as the cross-section and the location used in the building.

The following findings were obtained from the investigations.

1. The cascading potential for wood recovered from buildings should be considered from both the cross-section and the location
2. The independent parts in the building such as the roof and exterior cladding showed more potential for cascading
3. Smaller cross-section, for instance 1”×4” and 1”×6” with paint from the exterior cladding and 1”×4” from the roof board, showed high cascading potential and the paint seemed not necessarily critical to cascading
4. Technical aspects such as the demolition method and building design strongly affected the cascading potential. However, it was also considered that small improvements to the details could enhance the potential
5. Considering other types of wood products, cascading wood from buildings could be extended to other building not only with wood structure but also with steel or concrete structures

With respect to the first finding, the potential was initially analyzed by the cross-section and location separately. Through the analysis, however, it was shown that each cross-section and each location where the recovered wood was used had a different effect on the recovered condition. Therefore, it was concluded that the cascading potential needs to be considered from both aspects.

The potential for the expansion of a target for cascading can be expected. However, the second finding should be investigated further with the third and fifth findings because wooden roof truss and exterior cladding have also been applied to concrete or steel buildings as independent parts. Regarding the third finding, the necessity of developing suitable classification systems for cascading was also revealed.

The technical aspects mentioned in the forth finding are crucial and the whole building service life should also be taken into account, since building design, maintenance and demolition are strongly concerned with cascading. In this research, the joint details and the demolition method were mainly discussed. Therefore, these aspects should be investigated further in future research.

As the first case study, the potential amount for cascading from buildings could be viewed from different perspectives such as the cross-section, the location and the extent of damage caused by demolition. From the findings, the potential for wood recovered from the case study building was revealed.

5.2 Recommendations

At first, suitable demolition methods for cascading need to be defined as soon as possible because demolition of existing buildings is still on going. In addition to the methods, appropriate building design for cascading should be developed. This mainly aims to enhance the cascading potential of new buildings, however the design could also be applied to the renovation of buildings. It is even more profitable to investigate these methods and design together. Especially for the facilitation of cascading at the building level, creating a manual for demolition and design could encourage different stakeholders to pay more attention to cascading.

As discussed in other factors in chapter 4, more accurate cost comparisons are required to ensure the business feasibility. If it is profitable to cascade wood recovered from buildings, the industry should be naturally driven to that direction. Regarding this matter, several case studies have investigated the business feasibility and also discuss the predominance of deconstruction for cascading compared to demolition. However, the feasibility of cascading in Finland should be carefully examined with more case studies.

With respect to the business feasibility, life-cycle assessment (LCA) takes an important role as well. In the case that the whole process for cascading is environmentally more beneficial than the current demolition process, it would be much easier to apply an incentive system or tax reduction system to cascading recovered wood. These kinds of system could facilitate cascading and stimulate both the industry and the building owner to cascade materials from buildings.

In addition to these technological, economic and environmental points, political strategies have a strong influence on the facilitation of cascading. If all strategies are also supported by political approaches, they would be more effective. Social acceptance is required for users to be aware of cascading. Therefore, it can be said that social acceptance could be more efficiently speared by a combination of political and other approaches.

Subject to the limitation of the sample size in this research, the potential amount and the cascading potential for recovered wood from the case study building was revealed. In addition, the findings from this research could be concluded based on the assessment from the case study. However, it is recommended to investigate the results and findings with more case studies in future research. Furthermore, it would be more than interesting to discuss the feasibility of cascading recovered wood with an accurate cost comparison and LCA in future research.

6 SUMMARY

The amount of construction and demolition waste (C&DW) has been increasing and there are growing demands for a reduction of C&DW. Following this trend, the cascading of recovered materials has been actively discussed. In Finland, cascading wood recovered from building could be an effective approach to solve the problems since there are a lot of wooden buildings which need to be renovated or demolished. To discuss the potential, it is necessary to understand more detailed factors about recovered wood in building, such as the available amount, the types, the dimensions and the condition. With this information, possible cascading chains in Finland can be investigated and the prospect for the cascading of recovered wood in Finland can be discussed as well.

This study was structured in four steps as follows.

1. A review of previous research about cascading and related topics
2. An explanation about practical information of the target and method
3. An site assessment of the case study building and analysis of the data
4. A discussion of the potential for cascading wood in Finland

This research also aimed to define an reasonable and applicable method for monitoring and assessing demolition. For this reason, the following process was conducted during the assessment.

- Pre-visit to C&DW management site
- Pre-observation of other demolition project
- Defining the assessment method
- Inventory of the case study building
- Assessment of recovered wood on site

Based on these steps, the required data for wood recovered from the case study building was gathered and the results were analyzed.

The following results were discussed in order to reveal the potential for cascading wood recovered from the building.

- The actual amount of recovered wood from building demolition
- Detailed information of recovered wood
- The potential for the cascading of recovered wood
- A consideration of how to enhance the availablity of recovered wood

Based on the investigation of the result from different perspectives, the following findings were observed.

1. The cascading potential for wood recovered from building should be considered from the perspective of both the cross-section and the location
2. The independent parts in the building such as the roof and exterior cladding showed more potential for cascading
3. Smaller cross-section, for instance 1”×4” and 1”×6” with paint from the exterior cladding and 1”×4” from the roof board, showed high cascading potential and the paint was not necessarily critical for cascading
4. Technological aspects such as the demolition method and building design extensively affect the cascading potential. However, it was also considered that small improvements in the details could enhance the potential
5. Cascading wood from building could be expanded to other buildings, considering other types of wood products not only with wood structure but also with steel or concrete structures

The related factors were considered for the findings obtained. With respect to the first finding, it was shown that each cross-section and the location had a different effect on the recovered condition. The second finding indicated the potential for an extension of a target for cascading in the third and fifth findings.

Regarding the third finding, the necessity to develop a suitable classification system for cascading was found. The importance of the further developments on the technical aspects mentioned in the forth finding was pointed out.
As a result, the potential amount from buildings could be observed from different perspectives such as the cross-section, the location and the recovered condition. From the findings through the investigations, the potential for the wood recovered from the case study building was revealed.

To raise the reliability of the results, several topics for future research were recommended. First, further investigations on the technological aspects such as suitable demolition methods and building design for cascading were recommended. Following these, it was mentioned that both accurate cost comparisons and environmental assessments such as LCA on whole building life-cycle would be required to explore the business feasibility for cascading in Finland.

In the case that the whole process for cascading is environmentally more beneficial than the current demolition, it would be much easier to apply an incentive system or tax reduction system to cascading recovered wood. These kinds of system could facilitate cascading and stimulate both the industry and building owner to cascade materials from building.

In addition to these technological, economic and environmental points, political strategies have a strong influence on the facilitation of cascading. If all strategies are also supported also by political approaches, they would be more effective.

Subject to the limitation of sample size, the potential amount and the cascading potential for recovered wood from the case study building was discussed. In addition, the findings from this research could be concluded based on the assessment from the case study. However, it was recommended to investigate the results and findings with more case studies in the future research. Furthermore, it would be more meaningful to discuss the feasibility with accurate cost comparisons and environment assessments in future research.

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Appendix 1: Näsin Päiväkoti in Porvoo










Appendix 2: Amount of wood in element (Interior wall)

Interior wall	Size	Length (mm)	Number	Condition	Coments
W1 Inner stud at 1st	2"x3"	2550	9		600mm pitch 1 joint part 1 door
W1 Inner stud at 2nd	2"x3"	2550	9		600mm pitch
W2		2550	13		3 joint parts
W2		2550	13		
W3		2550	15		2 joint parts 1 door
W3		2550	15		2 joint parts 1 door
W4		2550	15		2 joint parts 1 door
W4		2550	15		Door parts included
W5		2550	15		Door parts included
W5		2550	15		Door parts included
W6		2550	12		2 Joint parts
W6		2550	12		2 Joint parts
W7		2550	12		2 Joint parts
W7		2550	12		2 Joint parts
W8		2550	6		
W8		2550	6		
W9		2550	6		
W9		2550	6		
Framing W1	2"x3"	4600	4		2 on top and bottom
W2		5800	4		
W3		3650	8		7350/2=3650
W4		6000	4		
		1500	4		
W5		6000	4		
		1500	4		
W6		5500	4		
W7		5500	4		
W8		3000	4		
W9		3000	4		

Appendix 2: Amount of wood in element (Partition wall)

Partition wall	Size	Length (mm)	Number	Condition	Coments
Inner stud W1	2"x3"	2550	5		600mm pitch
W2		2550	6		
W3		2550	7		small part 2 each included
W4		2550	3		small part 2 each included
W5		2550	4		
W6		2550	5		
W7		2550	9		
W8		2550	9		
W9		2550	8		corrner included
W10		2550	3		
W11		2550	3		
W12		2550	8		
W13		2550	33		
W14		2550	3		Door parts included
W15		2550	6		
W16		2550	13		
W17		2550	4		
W18		2550	7		
W19		2550	8		
W20		2550	5		
W21		2550	15		21" and 21""included
W22		2550	32		22" and 22"" 22""", vertical wall included
W23		2550	20		23" and 23"" 23""" included
W24		2550	15		24" and 24"" included
W25		2550	26		25" included
W26		2550	12		26" included
W27		2550	10		27" included
W28		2550	6		
W29		2550	12		29" included
W30		2550	26		30" included
W31		2550	4		
W32		2550	3		
W33		2550	4		
W34		2550	13		
W35		2550	20		35" included
W36		2550	4		
W37		2550	15		
W38		2550	4		
W39		2550	5		
W40		2550	6		
W41		2550	5		horizontal wall included

Appendix 2: Amount of wood in element (Partition wall)

W42		2550	5		
W43		2550	6		
W44		2550	5		
W45		2550	4		
W46		2550	7		
W47		2550	6		
W48		2550	10		
W49		2550	3		
W50		2550	6		
W51		2550	3		
W52		2550	11		
W53		2550	4		
W54		2550	4		
W55		2550	3		
W56		2550	10		
W57		2550	17		
W58		2550	4		58" included
Framing stud W1	2"x3"	2100	2		1 on top and bottom
W2		1800	2		
W3		2100	2		
W4		1100	2		
W5		1800	2		
W6		2400	2		
W7		5150	2		
W8		2900	2		
W9		4400	2		
W10		1200	2		
W11		1200	2		
W12		4250	2		
W13		1350	8		4 pieces
		4250	4		2 pieces
W14		1650	2		
W15		2300	2		
W16		3000	4		2 pieces
W17		2300	2		
W18		3950	2		
W19		3950	2		
W20		2700	2		
W21		2700	6		21" and 21""included
W22		2700	8		22" and 22"" 22"""included
W23		2700	8		23" and 23"" 23""" included
W24		2700	6		24" and 24"" included

Appendix 2: Amount of wood in element (Partition wall)

W25		5150	4		25" included
W26		3250	4		26" included
W27		2700	4		27" included
W28		2700	2		
W29		2700	4		29" included
W30		3500	8		30" included 7000/2=3500
W31		1900	2		
W32		1600	2		
W33		1900	2		
W34		3300	2		6600/2=3300
W35		3550	4		35" included
		1200	4		
		500	4		
W36		1800	2		
W37		4150	4		8300/2=4150
W38		1800	2		
W39		2700	2		
W40		2700	2		
W41		1900	2		
W42		2700	2		
W43		3000	2		
W44		2000	2		
W45		2000	2		
W46		3950	2		
W47		3000	2		
W48		5200	2		
W49		2200	2		
W50		4000	2		
W51		1650	2		
W52		3500	2		
		1200	2		
		700	2		
W53		2700	2		
W54		4100	2		
W55		1600	2		
W56		5550	2		
W57		4250	4		8500/2=4250
W58		1000	2		

Appendix 2: Amount of wood in element (Exterior wall)

Exterior wall	Size	Length (mm)	Number	Condition	Coments
Cladding N	1"x6"	2900	82	Painted	
	1"x4"	2900	82	Painted	
Cladding S	1"x6"	2900	93	Painted	
	1"x4"	2900	93	Painted	
Cladding E	1"x6"	2900	88	Painted	
	1"x4"	2900	88	Painted	
Cladding W	1"x6"	2900	81	Painted	
	1"x4"	2900	81	Painted	
Cladding entrance part NS Vertical	1"x6"	850	32	Painted	Upper and down, 2 sides
		950	32		
	1"x4"	850	30	Painted	Upper and down, 2 sides
		950	30		
Cladding entrance part NS Horizontal	1"x4"	3000	96	Painted	
Cladding short window part	1"x6"	850	144	Painted	8 claddings/ windos N7 S6 E4 W1
		950	144		
	1"x4"	850	126	Painted	7 claddings/ windos N4 S4 E2 W3
		950	126		
Cladding longer window part	1"x6"	850	221	Painted	17 claddings/ windos
		950	221		
	1"x4"	850	208	Painted	16 claddings/ windos
		950	208		
Cladding attached part	1"x6"	500	252	Painted	Average length , 6 attached part
	1"x4"	500	246	Painted	
Cladding roof part vertical NSEW	1"x4"	550	390	Painted	6 attached part
Cladding roof part Horizontal NS	1"x4"	4450	40	Painted	5 cladding , 8900/2=4450, N and S
Rafter furring strips NS	1"x4"	4450	8	Painted	2 parts with same length
Rafter furring strips attached part	2"x4"	3900	12	Painted	6 attached part
Cladding roof part Horizontal EW	1"x4"	3000	20	Painted	5 cladding each 6000/2=3000, E and W
		2500	40	Painted	5 cladding each 10000/4=2500, E and W
		2900	20	Painted	5 cladding each 5800/2=2900, E and W
Shorter window part	1"x4"	1500	26	Painted	Entrance part 4 windows in one side
		1500	26	Painted	Entrance part 4 windows in one side
Longer window part	1"x4"	3000	13	Painted	
		1500	13	Painted	
Door frame part	1"x4"	1500	9	Painted	
		2250	18	Painted	2 in one door
Frame attached part NS	1"x6"	4450	8	Painted	
Frame attached part EW		3000	20	Painted	Outer line framing
		2500	40	Painted	
		2900	20	Painted	
corner cladding	1"x6"	2800	8	Painted	2 claddings in each entrance part
corner cladding entrance part		3000	4	Painted	
Rafter furring strips EW	1"x4"	3000	4	Painted	
		2500	8	Painted	
		2900	4	Painted	
Inner stud N	2"x3"	2900	33		1500mm pitch, 2 studs in 11 joint part
Inner stud N window part		600	3		Upper and down of 3 window parts
		650	3		
Inner stud S	2"x3"	2900	32		

Appendix 2: Amount of wood in element (Exterior wall)

Inner stud S window part		600	4		
		650	4		
Inner stud E	2"x3"	2900	15		1500mm pitch, 2 studs in 3 joint part
Inner stud E window part		600	3		
		650	3		
Inner stud W	2"x3"	2900	16		1500mm pitch, 2 studs in 3 joint part
Inner stud W window part		600	2		
		650	2		
Button N	2"x2"	1500	5		
		1200	5		
		1200	5		
		2700	5		
		1400	5		
Button N window part	2"x2"	3750	12		small window 1500mm large 3000mm 7500/2=3750
		3000	6		3 doors
		3750	12		7500/2=3750
		4500	6		
Button N Door part	2"x2"	1500	6		3 doors
Button S	2"x2"	1800	5		
		2900	5		
		1600	5		
		1600	5		
		1600	5		
Button S window part	2"x2"	3000	6		small window 1500mm large 3000mm
		3750	12		7500/2=3750
		6000	6		
		4500	6		
Button S Door part	2"x2"	1500	8		4 doors
Button E	2"x2"	6000	5		
		6000	5		
Button E window part	2"x2"	3000	6		small window 1500mm large 3000mm
		4500	6		
		3000	6		
Button E Door part	2"x2"	1500	2		1 door
Button W	2"x2"	3000	5		
		3200	5		
		4300	5		
Button W window part	2"x2"	3000	6		small window 1500mm large 3000mm
		4500	6		
		4500	6		
Button W Door part	2"x2"	1500	2		1 door
Framing stud N	2"x3"	3000	24		1 on top and bottom
Framing stud S		3000	24		
Framing stud E		6000	8		
Framing stud W		6000	8		

Appendix 2: Amount of wood in element (Floor and ceiling)

Floor	Size	Length (mm)	Number	Condition	Coments
Wood joist	2"x8"	3000	400		600mm pitch 46 unit- 1,5
steel joist	2"x8"	6000	96		46 unit

Ceiling	Size	Length (mm)	Number	Condition	Cooments
Innser stud	2"x8"	3000	400		600mm pitch same as 3000mm floor joist
Stud	2"x2"	6000	267		600mm pitch 46 unit and 2 next to steel
		3000			

Appendix 2: Amount of wood in element (Roof)

Roof	Size	Length (mm)	Number	Condition	Coments
Roofing board NS	1"x4"	3000	1372		100mm pitch, central part=6 Nand S
Roofing board NS edge part		1200	140		North and south
Roofing board EW		3000	666		100mm pitch East and West
Roofing board Ew edge part		1200	140		East and West
Rafter reaching diagonal	2"x5"	4500	20		2 rafters in 1 corner 9000/2
		4250	8		2 rafters in 1 corner 8000/2
		3500	8		2 rafters in 1 corner 7000/2
		3000	8		2 rafters in 1 corner 6000/2
		2500	8		2 rafters in 1 corner 5000/2
		3900	8		2 rafters in 1 corner
		3000	8		2 rafters in 1 corner
		2000	8		2 rafters in 1 corner
		1000	8		2 rafters in 1 corner
Rafter diagonal	2"x5"	4400	4		Total length=13120
Rafter EW	2"x5"	4700	28		Total length=9400 9400/2=4700
Rafter NS		4350	84		Total length=13000 13000/3=4350
Rafter NS central part	2"x5"	4350	20		Total length=10500 10500
Rafter NS central part short		1800	10		10500-4350*2
Rafter attached part NSEW	2"x5"	2850	4		5700/2=2850
		1850	4		3700/2=1850
		800	4		1600/2=800
		5000	12		6 attached part
Beam	4"x4"	4350	92		1500mm pitch 8700/2 North and south
Beam central part		3150	35		6300/2=3150 From east to west
Ridge beam	2"x5"	4075	2		In the center, total length 8150/2 W
		3150	2		length 6340/2 East side
Basic pillar	2"x4"	400	108		1000mm pitch 2 sides
		800	100		2 sides
		1150	84		2 sides
		1550	76		2 sides
		1900	60		2 sides
		2300	38		2 sides
		2750	38		2 sides
		3000	22		1 side center part 2 in one side
Diagonal pillar	4"x4"	400	4		4 edges
		800	4		4 edges
		1150	4		4 edges
		1550	4		4 edges
		1900	4		4 edges
		2300	4		4 edges
Furring strip NS	1"x4"	6000	108		From 5 row, 2 strips

Appendix 2: Amount of wood in element (Roof)

Furring strip EW	1"x4"	6000	44		From 5 row, 2 strips
Brace EW 2-3rd row Horizontal	1"x4"	1600	12		N and S
		1800	12		N and S
Brace EW 4-5th row Horizontal		1950	6		N and S
		2150	6		N and S
Brace EW 1st row Vertical	1"x4"	1100	10		Same length for cross X
Brace EW 2nd row Vertical		1300	10		Same length for cross X
Brace EW 3rd row Vertical		1550	10		Same length for cross X
Brace EW 4th row Vertical		1850	10		Same length for cross X
Brace EW 5th row Vertical		2150	6		Same length for cross X
Brace NS 2-3rd row vertical		1600	18		E and W
		1800	18		E and W
Brace NS 4-5th row vertical		1950	10		E and W
		2150	10		E and W
Brace NS 1st row Horizontal	1"x4"	1100	28		Same length for cross X
Brace NS 2nd row Horizontal		1300	28		Same length for cross X
Brace NS 3rd row Horizontal		1550	28		Same length for cross X
Brace NS 4th row Horizontal		1850	28		Same length for cross X
Brace NS 5th row Horizontal		2150	20		Same length for cross X
Brace NS 6th row Horizontal		2500	20		Same length for cross X
Brace NS 7th row Horizontal		2950	16		Same length for cross X
Brace NS 8th row Horizontal		3150	16		Same length for cross X